Semiautomatic Three-dimensional Reconstruction and Quantitative Analysis of Pulmonary CT Scans:

Current Methodology

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Note

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the Department of the Army or the Department of Defense.

The mention of specific products does not constitute an endorsement.

In conducting the research described in this report, the investigators adhered to the Animal Welfare Act and other federal statutes and regulations relating to animals and experiments involving animals and with the Guide for the Care and Use of Laboratory Animals, National Institutes of Health Publication 85-23. The Animal Care and Use Committee of our Institute approved the experimental protocol and animal care.

Abstract

Assessment of density patterns is critical for quantification of the morphology in healthy and diseased lungs. We propose a fast and accurate method for semiautomatic lung density distribution assessment. The algorithm is based on a customized, commercially available software package that supports various file formats. Analysis of porcine CT scans was done using a software package, Able Software Corp., 3D-Doctor, Lexington, MA. Briefly, axial CT scans were semi automatically analyzed, slice-by-slice, using the interactive segmentation function of the 3D-Doctor software. Pre, and post, contusion image stacks were quantified and compared with respect to density distribution. The pulmonary parenchyma was interactively segmented employing 5 regimens. Each of the regimens represented a window of Hounsfield units (HU) corresponding to level of aeration of the parenchyma as reported by Gattinoni et al. Air (HU value –1000), hyperinflated areas (HU window from –998 to –902), normally aerated areas (HU window from –900 to –500), poorly aerated areas (HU window from –498 to –100) and non-aerated areas (HU window from –98 to +100) were defined in each of the slices for each of the lungs. The resulting data were represented with respect to number of pixels, total density, mean density, object histogram as well as surface area and volume data for each of the objects. 3-D reconstruction was performed via simple surface rendering by the program. 3-D- reconstructed rotational images were available to display areas and regions of the analyzed lung parenchyma both as a whole and in separate with respect to aeration and density distributions. Areas of use in military and civilian setting are proposed.

Introduction

With the introduction of CT-scanners, our ability to quantify changes in lung densities associated with pulmonary diseases increased tremendously. Early CT scan-based pulmonary research established normal and abnormal patterns of density distributions within the lung parenchyma. Rosenblum and Wegener et al. in the late 1970s offered insight into the normal lung density distributions revealed by CT scan, with respect to body position, respiratory phase and age. In general, comparison of conventional chest radiography to computed tomography offered the following advantages:

- assessment based on conventional radiography was found to be largely subjective and reliable mostly for gross estimations
- conventional radiographs are less sensitive to diffuse disease processes than localized lesions
- density estimations can not be reliably drawn based on conventional X-ray
- conventional chest radiography was reported to underestimate the actual degree of pulmonary injury

In contrast, CT offered improved:

- contrast resolution
- transaxial view of anatomy
- dynamic range

With these early studies the superiority of CT as a tool for detection of diffuse morphological changes in pulmonary diseases became obvious. Furthermore, with the

development of more sophisticated CT equipment and increasing involvement of informatics in the acquiring and processing of medical imaging, it became apparent that human involvement will be diminished in the data acquisition and interpretation systems of the future.

Currently many equipment vendors offer extensive personal computer (PC) based CT interpretation systems that, in many cases, include three dimensional reconstruction capabilities. Most of these programs work solely in conjunction with the particular vendor's equipment and support proprietary imaging standards, thus creating considerable compatibility challenges.

Previously, the most widely used approaches to lung density estimations were the so-called sector method and the whole-lung method. In the sector method, the overall mean density of a lung is estimated from averaging Hounsfield (HU) values of 14 regions of interest: 3 regions of interest defined in a base cut CT scan (immediately above the diaphragm), 3 in the mid-thorax cut (carina level) and 2 in the apex cut (level of the sternoclavicular joint). In the whole-lung method, the entire lung fields of the above-mentioned 3 cuts are studied and the six values (right lung, left lung in each cut) are averaged to come up with the mean lung density. The advantage of these methods is that any grey scale density estimation procedure can be used for this analysis (for example, with Osiris Imaging Software, Digital Imaging Unit, University Hospital of Geneva, Geneva, Switzerland), and acceptable mean grey scale density estimations can be made. The disadvantage of these methods is that they are extremely time- and labor-consuming, are of limited accuracy, and cannot serve as a basis for precise density quantification and morphology-based diagnostics.

In 2001 we introduced and developed a semiautomatic algorithm for pulmonary CT scan segmentation, quantification and density-based diagnostics which is fast, accurate and widely usable for evaluation of high volumes of pulmonary CT scans in research and clinical practice. The technique is based on a commercially available software package, - 3D-Doctor (Able Software Corp., Lexington, MA), that supports a wide range of image types and standards. For lung CT analysis the software was modified to our specifications.

The purpose of this report is to provide a tutorial on the pulmonary quantification procedure as currently practiced at this Institute. The intent is to enable an investigator who is new to the field to successfully implement the technique with minimal assistance. Given that the technique is an adaptation of commercially available software, which is an extensive 3-D imaging, rendering and modelling resource, by no means do we claim this manuscript to be a comprehensive tutorial on the software itself, but rather a set of instructions on adapting the tool for this particular application. For those interested in extensive insight into the 3-D Doctor software, we recommend referring to the manual and/or arrangement of training courses with Able Software Corporation.

Other 3D software packages are commercially available however we did not examine all of these programs in detail during development of the procedures described in this manuscript.

Basic Considerations and Assumptions

When estimating CT scans of diseased lungs by eye most of radiologists use the Fleishner Society Nomenclature Committee description of morphological CT patterns (Austin et al., 1996). These patterns are as follows:

1. **ground glass opacification:** defined as a hazy increase in lung attenuation, with preservation of bronchial and vascular margins
2. **consolidation:** a homogenous increase in lung attenuation that obscures bronchovascular margins in which an air-bronchogram may be present
3. **reticular pattern:** innumerable, interlacing line shadows that may be fine, intermediate, or coarse

In reference to different lung diseases these morphological patterns can have different pathophysiological meanings, and varying terminology might be used to describe a similar change in density distribution within the lung parenchyma.

Whatever terminology may be used, it takes an experienced radiologist to differentiate these features. As a consequence, the subjective view of the experienced specialist will be perceived as an objective basis for diagnosis. What further complicates the reliability of this analysis is the fact that the knowledgeable specialist has to analyze large numbers of CT scans and, although a gross or qualitative estimation is not a difficult task, accurate quantification of the diffuse morphologic features is impossible. Furthermore, in case of pulmonary contusion, though contusion size estimation by eye can be done, contusion volume assessment cannot.

Based on the above, an automated and quantitative method of assessing pulmonary CT scans would be very useful. This would not only save time and human resources but, at the same time, could offer an accurate and reliable way of assessing morphology that could revolutionize diagnostics and prognostics in pulmonary medicine.

The relationship between physical density, the attenuation value and Hounsfield units

Pulmonary tissue is inherently inhomogeneous. Simplified, it is represented by the densities of water, air and lung tissue. Overall, the density distributions vary with body position, as reported by Rosenblum et al. in 1978. The density of the lung decreases with inspiration and increases with expiration. In a normal supine subject the density increases linearly with anteroposterior distance because of gravitational forces.

Voxel. The CT unit of volume

As described by Gattinoni et al., in a standard 10 mm axial image the volume of a voxel is 1.5 x 1.5 x 10 mm = 22.5 mm^3. This is approximately the volume of a normal acinus (containing 2000 alveoli) at functional residual capacity (FRC). Due to the difference in shapes (the voxel is a parallelepiped and the acinus is a sphere) and topographic position, the voxel and acinus do not line up perfectly. Furthermore, at increasing inflation the acinus increases in size and this leads to fewer of the acini being included in each voxel. On the other hand, 15 –20 normal but collapsed acini may be

included in a single voxel. Additionally, many voxels may include denser structures like blood vessels, lymphatics and airway structures.

Smaller voxel size (CT scanners of recent generations) improves the accuracy of CT–based density estimations, as they increase spatial resolution and decrease volume averaging.

The ratios of lung tissue, blood, and air in each voxel define the physical density of the lung.

Relation between physical density and attenuation coefficient

Per Rosenblum, the linear attenuation coefficient for lung parenchyma is primarily determined by the physical density (ρ) and the electron density (Ng) i.e. (ρ x Ng). The electron density is constant for biologic tissues so the equation defining the approximate lung density was proposed to be:

$\rho(\text{lung}) = (\text{AV}) / 1000 + 1$, ρ - expressed as g/cm^3

where AV is attenuation value expressed in CT number (Hounsfield units). See next chapter.

Thus, an attenuation value of – 800 HU is proportional to a density of 0.2 g/cm^3.

Attenuation value (coefficient)

The X-ray attenuation of a tissue is expressed by CT numbers, also called Hounsfield units (HU). The HU represents the percentage of radiation absorbed by the lung tissue in any given voxel. The greater the absorption, the less radiation hitting the CT detector and the smaller the number. For reference, the attenuation scale assigns

+1000 HU for bone, 0 for water and – 1000 for air. Blood and tissue are between 20 and 40 HU.

Assuming that the specific gravity of tissue is 1, Gattinoni proposed the following relationship between density in any given lung region:

$$\frac{\text{Volume}_{\text{gas}}}{(\text{Volume}_{\text{gas}} + \text{Volume}_{\text{tissue}})} = \frac{\text{Mean CT number}_{\text{observed}}}{(\text{CT number}_{\text{gas}} - \text{CT number}_{\text{water}})}$$

Hence, knowing the CT number frequency distribution for a given region of interest and its total volume (volume $_{\text{tissue}}$ + volume $_{\text{gas}}$), it is possible to compute the amount of tissue (lung tissue + blood + extracellular water) for each compartment of interest

Lung compartments and CT frequency distribution

The CT pulmonary units (voxels) are distributed across the lung as a function of their physical densities. As reported by Gattinoni, Vieira and other groups, CT number frequency distribution analysis is usually performed on an 11-compartment scale covering the range of HU values from –1000 to +100. In our analysis, we used the pooled data from several investigator's groups to define the HU windows, binned down from the initial 11 compartments to 4 as reported by Gattinoni et al (1988) and Vieira and coworkers (1998). There seems to be a consensus in literature in reference to consideration of the lung compartments reflecting various degrees of parenchymal aeration. These are:

- Hyperinflated areas
- Normally aerated areas

- Poorly aerated areas
- Non aerated areas

For HU window values we adopted the data published by Gattinoni, Vieira and colleagues, assigned as follows:

TYPES OF LUNG TISSUE WITH RESPECT TO AERATION	**HOUNSFIELD UNIT WINDOW**
Air	–1000
Hyperinflated	–1000 to - 900
Normally aerated	–900 to –500
Poorly aerated	–500 to –100
Non aerated	–100 to +100

Due to the nature of our study (occurrence of pneumothoraces) we added an additional “Air” compartment with categorical –1000 value to define it. These compartments and the HU window values defining them served as the foundation for our semi-automated quantification method, described further in this manuscript.

Image Acquisition, Storage and Management

Our work was based on the pulmonary contusion model originally developed by Proctor et al. and introduced to this Institution by us in 2001.

Briefly, anesthetized female Yorkshire pigs were used for the study. The study involved CT scan acquisition at 2 time points: before injury and 6 hours after injury enabling the comparison of density distributions in a normal and pathologic lung of the same subject. The injury was inflicted in the right side of the chest, centered around the point of intersection of a perpendicular drawn from the base of the xiphoid to the midaxillary line. The injury consisted of an impact against the chest wall caused by a round, 7.5 cm-diameter, flat-surfaced steel plate, powered by a captive-bolt cartridge-charged device.

The CT scans were acquired using the Philips Tomoscan CT scanner (Philips Medical Systems, Eindhoven, The Netherlands) located in the Laboratory area of the Institute.

Images were taken at a 10 mm slice width with no interslice distance. The exposures were taken at 120 kV and 40 mA. The CT scanner was calibrated using the standard phantoms provided by the vendor. At the designated time points the subject, while on ventilator and under intravenous anesthesia, was taken to the CT scanner and a series of axial 10 mm slices were acquired on inspiratory breath hold. The images were stored in DICOM 3 format in an image server of the Brooke Army Medical Center Department of Radiology (General Electric MDIS/PACS system). Images were queried

and retrieved from the image server using JDicom software

http://www.tiani.com/JDicom/) and were stored on a computer.

3-D Image Analysis Software

General information about the 3D-Doctor software and its applications is available from the users manual and/or from http://www.ablesw.com/3d-doctor/. In this section we would like to discuss some details specific to our application.

As a result of our recommendations, a new version of the program was released in which the structure of automated functions and operational window alignment enabled continuous slice-by-slice segmentation analysis of lung parenchyma to be done faster and with minimal operator involvement.

In a brief overview the algorithm is as follows.

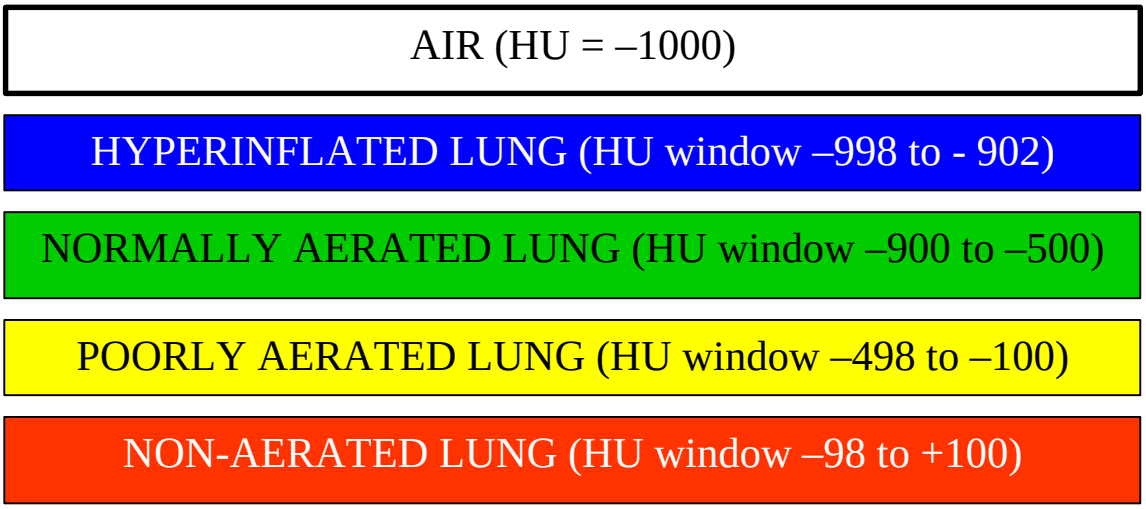
The raw DICOM images are loaded into a list file as a sequence of images. The list file should be opened from the program and, by doing so, a project is started that should be saved as a project file using the “Save” menu. When a project file is created it can be opened with the analysis results saved into it. The project file is the processed data file. The list file and raw data are not used after a project file exists. When the images appear in the view windows, select the first one (numbered “0”) from the list of images in the right side of the screen. Segmentation of this first image will be done followed by the next images in the stack. The process of segmentation is described in detail in the “Step-by-step Instructions on Semiautomatic Quantification of DICOM CT Scans” section.

An object is an image or part of an image that is being analyzed. In our case, each part of the lung with differing density/aeration levels was considered a separate object. Objects can be named as desired. For porcine pulmonary CT scan analysis we used the

following object names that were abbreviated and entered into the “Object management menu”:

- Right lung normally aerate – RN
- Right lung hyperinflated – RH
- Right lung air – RA
- Right Lung poorly aerated – RP
- Right lung non-aerated- RNON

The same principle was followed with naming of objects in the left lung. In each of the slices in the stack, these objects were outlined and after the corresponding HU windows were applied, analyzed. The HU window is applied via entering the low- and high cut off values into the segmentation window. After the values are entered, the software outlines all the areas, within a CT scan region of interest, drawn by the operator, where the densities fall within the specified limits for the object under analysis. This phase is easy. However, it is important to note that the minimum step between two HU values to be entered in the segmentation window of the software is a value of 2. For example, when separating the normally ventilated areas (HU window form –900 to – 500) from the poorly ventilated areas (HU window of – 500 to –100) the operator needs to enter – 498 instead of – 500 as the lower cut-off value for the poor area in order to achieve full separation between analyzed objects (HU windows). Thus, the window values used in our study (values entered into the segmentation window) were:



We believe that the volume and mean grey scale density (MGSD) estimation inaccuracies attributed to this above- mentioned phenomenon were negligible.

Depending on image quality and resolution, the operator might need to apply some of the manual editing tools available. Use of these tools is self-explanatory and provides an excellent resource in eliminating artifacts from analysis.

Methodological limitations

The technical limitations of accurate CT–scan analysis can be summarized in 3 groups:

1. Image-quality-related
2. Subject-related
3. Analysis-related

Image-quality-related limitations

Contemporary CT scanners enable high image –volume, fast and low –irradiation data acquisition, consequentially improving safety and spatial resolution. Obtaining a higher volume thus smaller sliced CT scans will enable finer data processing.

Subject-related limitations

The data acquisition can be obtained at various phases of lung tissue aeration depending on the focus of the problem studied. Obviously, image acquisition at FRC and full inspiration will result in systematically different density values as a function of higher aeration of the lung. A consistent and outcome dependent approach should be considered in every case.

By design, in the scenario of our experiment we performed CT scanning at full inspiration thus somewhat artificially decreasing our mean HU values.

Subject position (forces of gravity) as well as immobility and degree of cooperation (for conscious studies) might introduce some degree of error. In our study the subjects were medically “immobilized” by means of deep general anesthesia.

Analysis-related limitations

The better the image resolution, the more accurate the volume estimation by simple surface rendering. Likewise, better image resolution improves differentiation of HU windows with attenuation values close to each other, as well as between anatomical structures within a given range of attenuation values.

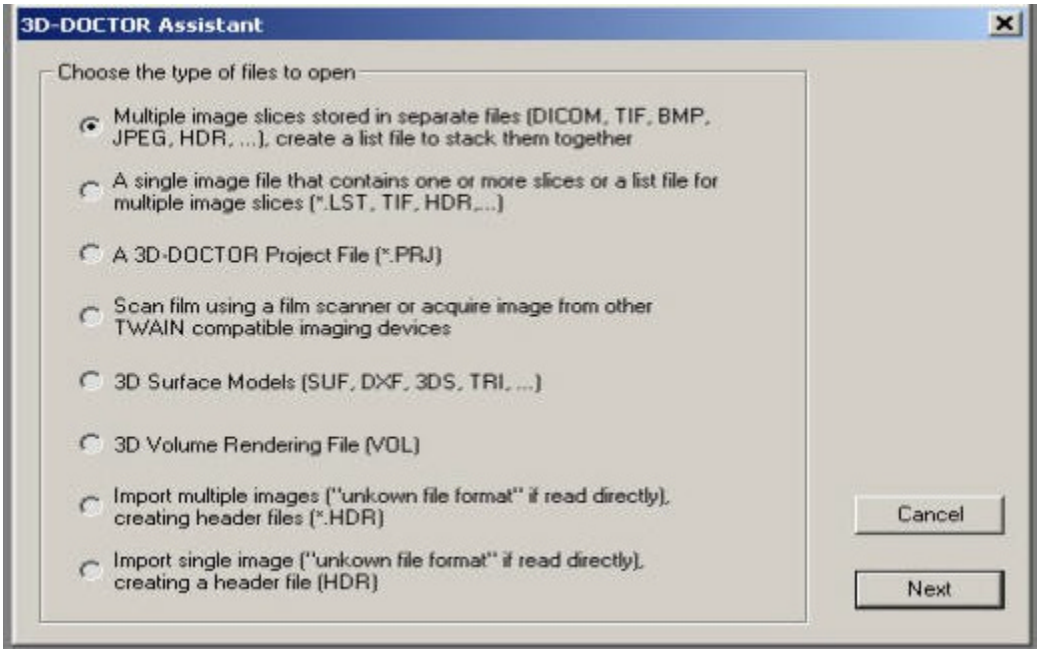
An example of the former would be when a poorly ventilated area with its low cut off value of “– 100” would be more readily graphically separated and differentiated from a non-ventilated area for which “ – 100” is its high HU cut off value.

Regarding our experience with differentiation of structures within a window of attenuation values. The quality of the images we acquired did not allow us fine differentiation between normal anatomical structures with high attenuation values (respiratory tree, vessels) being included inside poorly and to a greater extent inside non-ventilated areas. Defining and manually editing these normal anatomical structures inside intact lung is possible however our resolution did not allow “seeing” these areas after the contusion inside the non - ventilated areas. Thus the non-ventilated areas in the post contusion CT scan data sets included normal anatomical structures. This led to the mean density of the non-ventilated areas to be somewhat artificially increased, as well as the overall volume of the non-ventilated compartment was somewhat (minimally) higher due to the densities of the added structures.

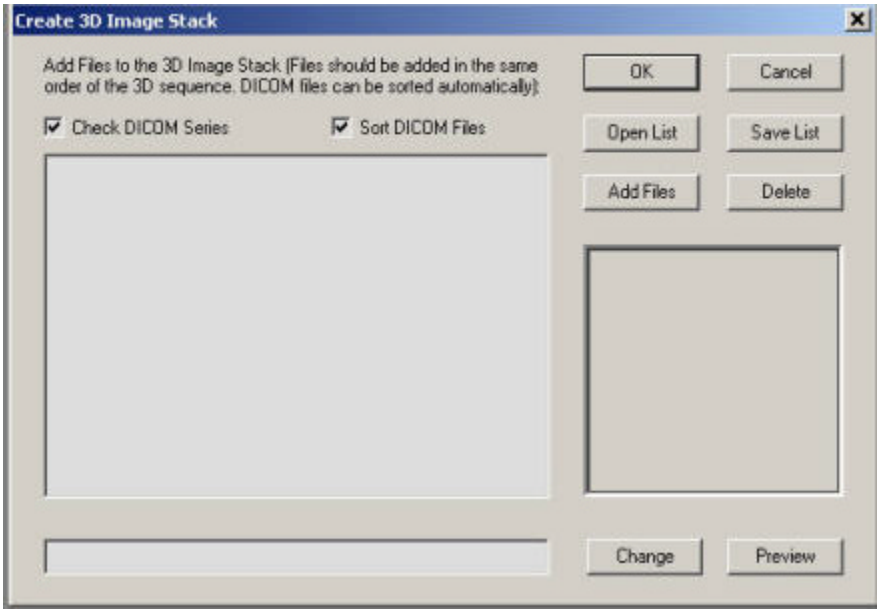
Step-by-step Instructions on Semiautomatic Quantification of DICOM CT Scans

Part one: Opening DICOM stacks, saving CT stacks and creation of a list and project files. Object management window.

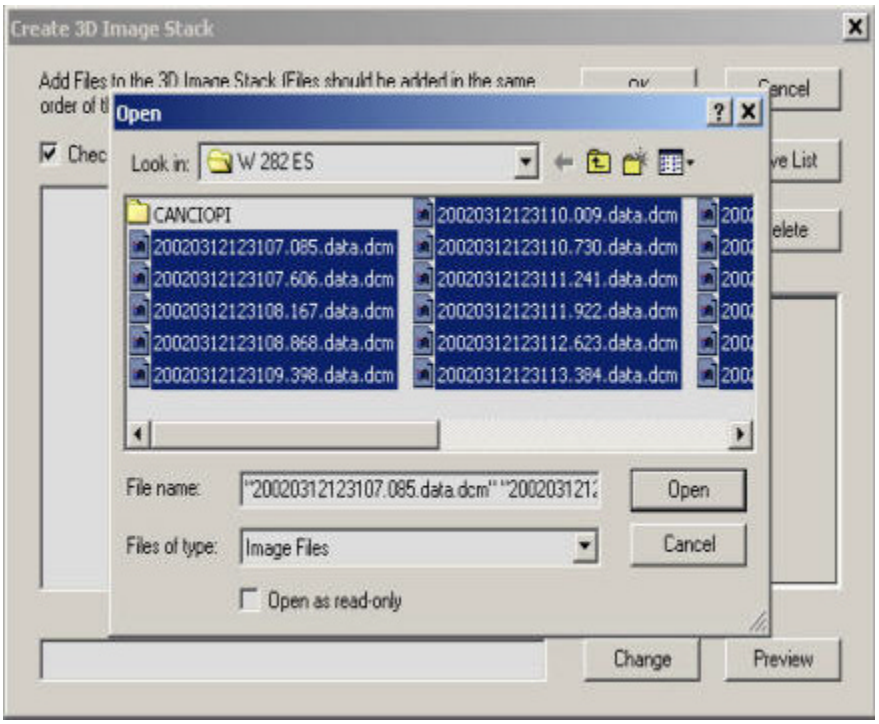
1. Open 3- D Doctor double clicking on the icon.



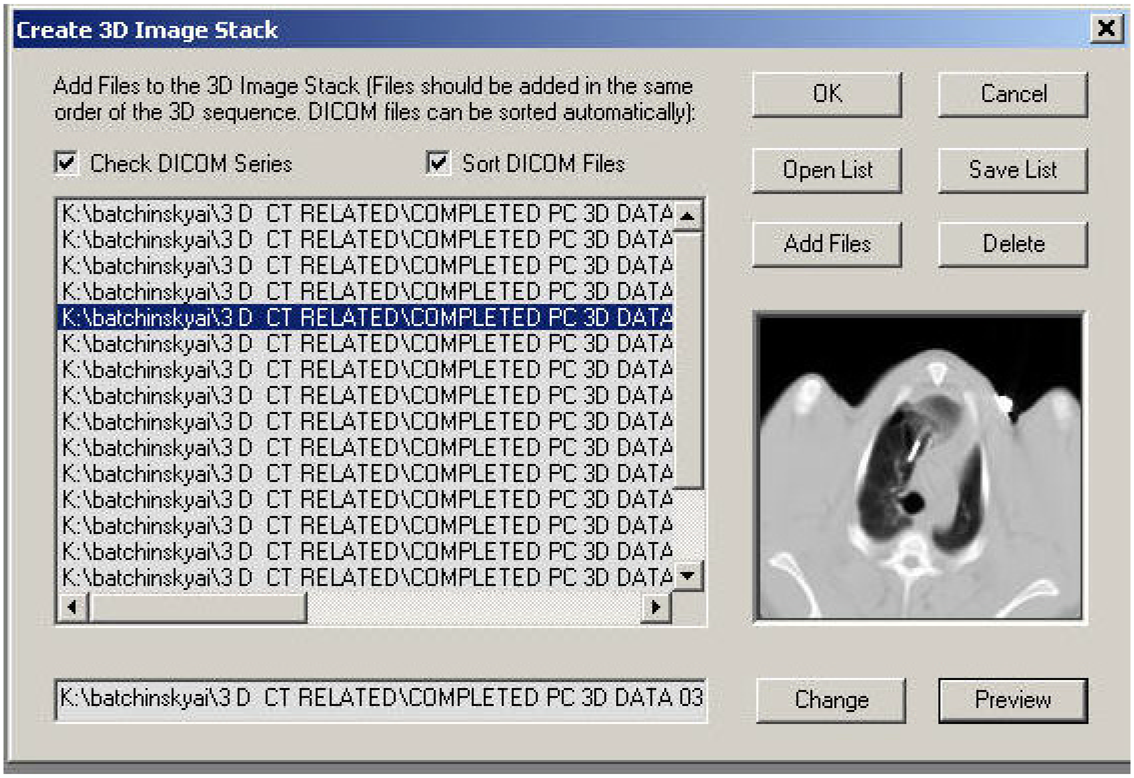
2. In the first menu choose “Multiple image slices …” Click “Next”. The below-depicted window will appear.



3. Click on “Add files” and select the source for the DICOM files to be added to the list file. Add the desired files by holding the “Control” button on the keyboard and left-clicking on the images one-by-one. If you don’t do this the images will be included into the list without sequential order.

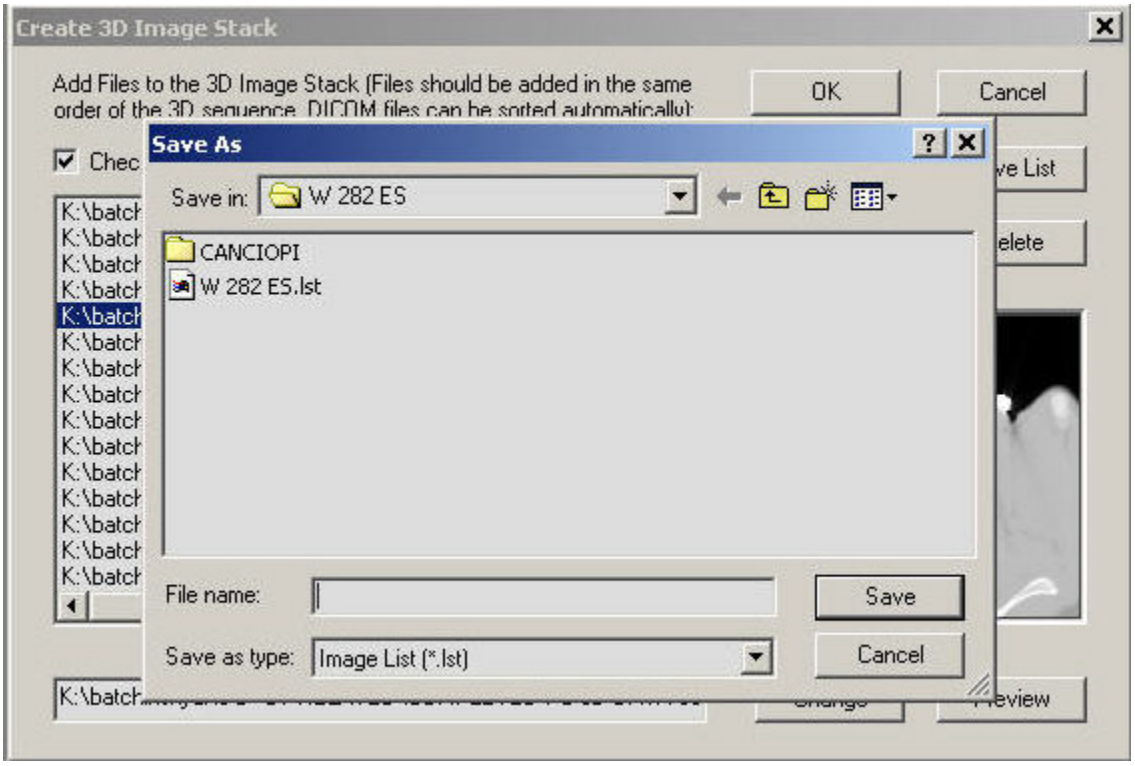


When doing so, one can preview the selected images by highlighting and clicking on the “Preview” button as shown below.



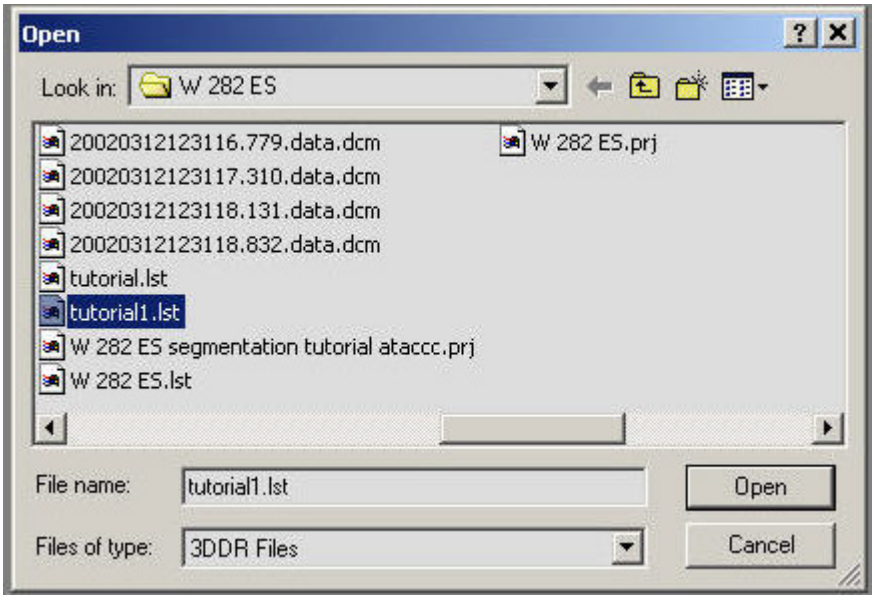
The user can also add/delete files from the stack to be included in the list using the menu buttons in the window.

When you are finished selecting and editing you list file click "Save list".



As a rule, the list file is saved into the same folder where your raw images are located.

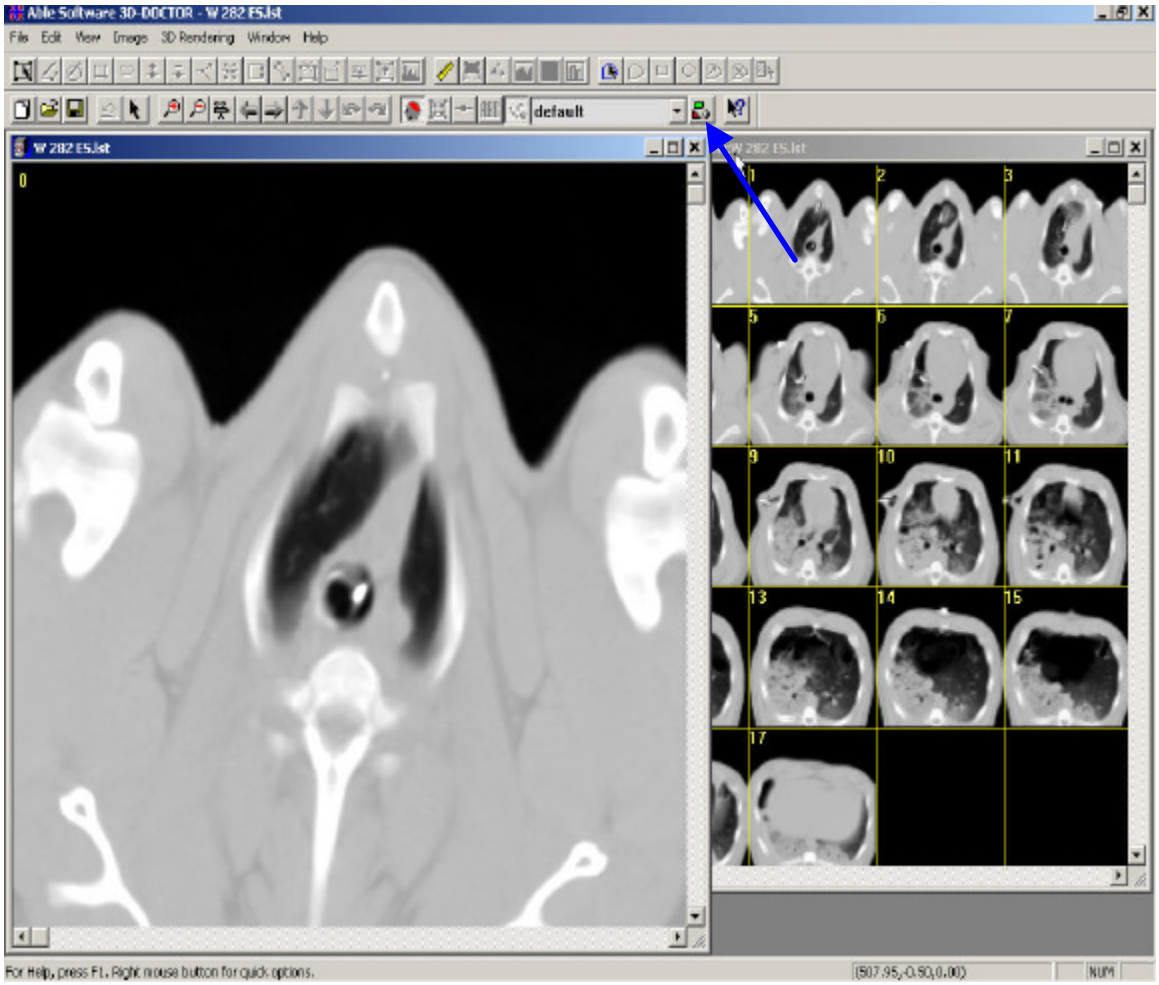
4. Open list to be analyzed by double clicking on its name.



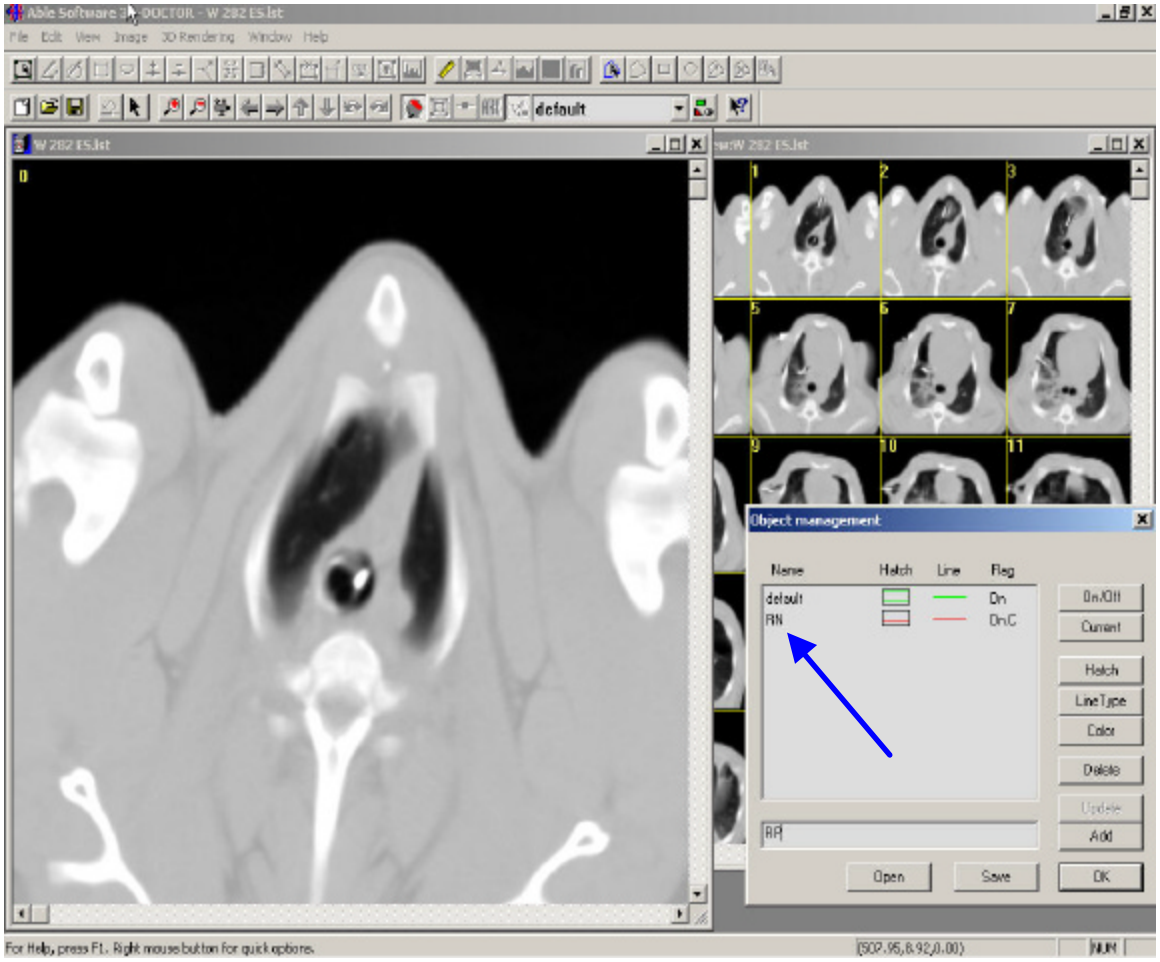
When you see the images in the view windows choose "Save Project" in the Save

menu and save the project with the desired name. Always save your work during analysis.

5. Next, we create an object list. Click on the little "Set Object" icon located in the toolbar next to the "Help" icon.

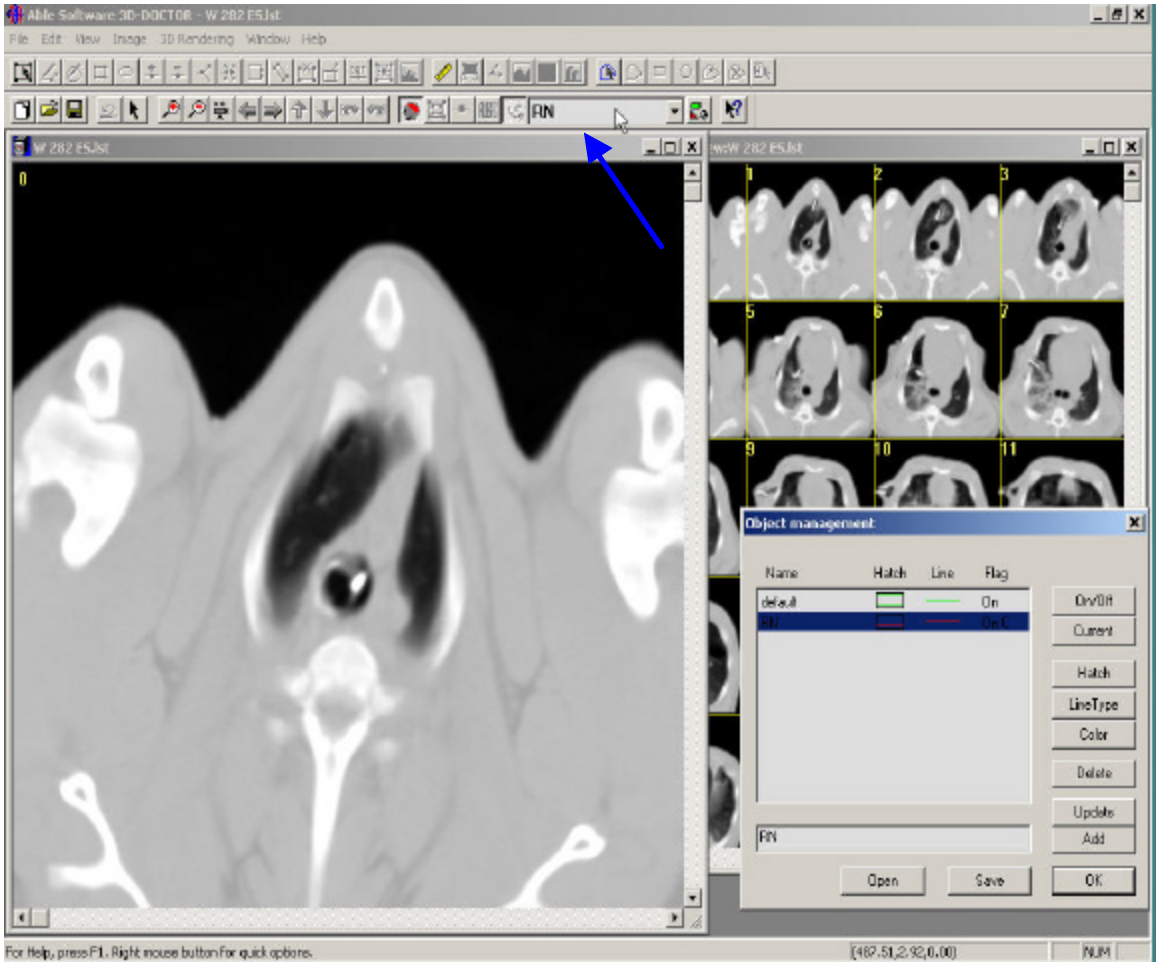


6. In the appearing object management dialog box type in an abbreviated name for normally aerated right lung, for example – RN. Click "Add"



and it will appear on the general list in the upper window of the object management menu under the "default" object. Using the line type, color and hatch buttons you can modify the features of the selected object to be displayed on the segmented CT scan. It is advisable that you differentiate each object using color, line type or else. The On/Off button will specify if the selected object/objects are active and displayed in the window and the Current button will select one object to be the currently active so that the segmentation results will be assigned to this object. Setting the RN as current will be reflected in the appearance of this

object's name in the current object window immediately to the left of the "Set object" button.



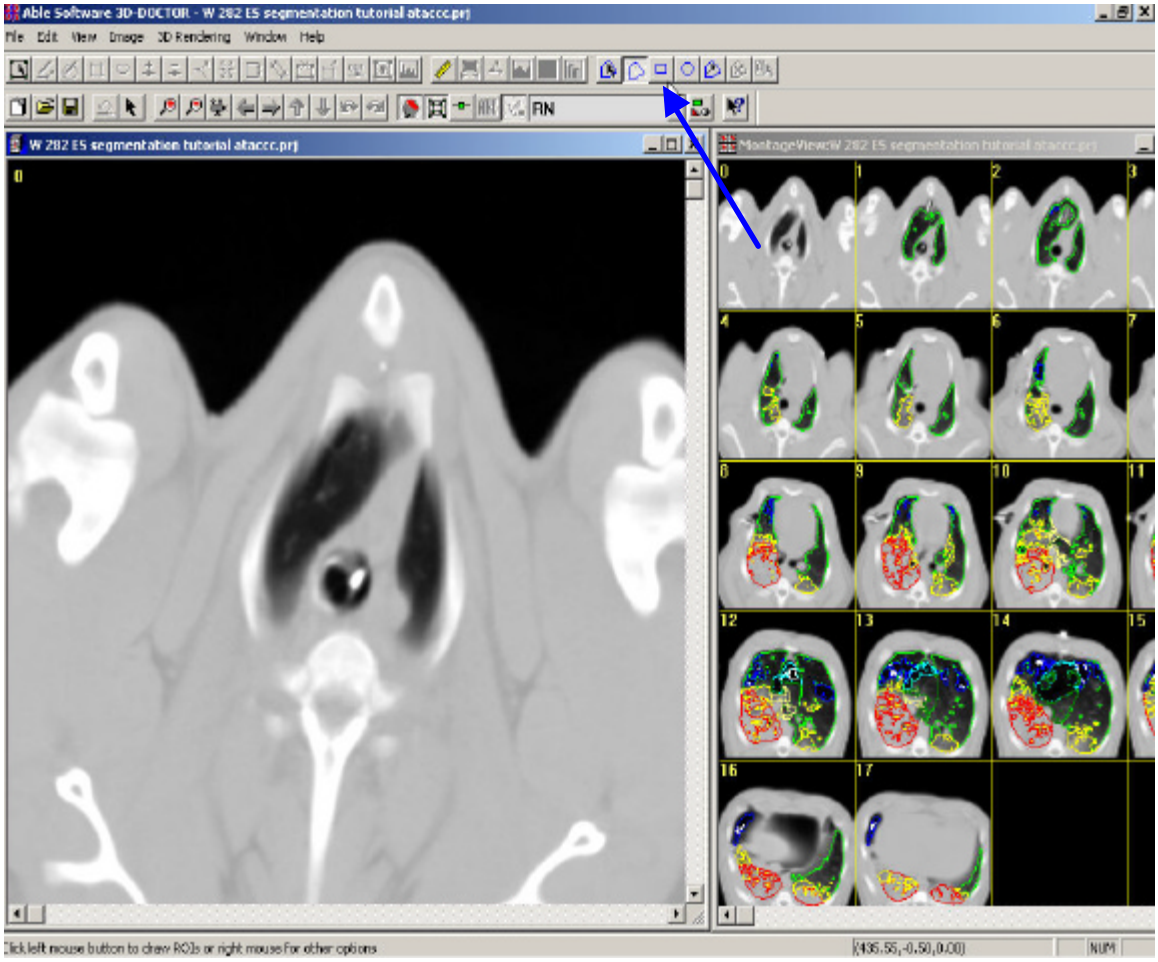
If repeated analysis will take place i.e. if stacks from different subject within the same study will be analyzed the Object settings can be saved and loaded to the next project file using the "Save" and "Open" buttons of the "Object Management" window.

After the above steps save your project file is containing the "Object Management" settings and you are ready for the segmentation.

Part two: segmentation

1. Open a project file.
2. From the Montage view screen on the right side of the screen select the image you will be analyzing by double-clicking on it.
3. In the “Object management” window select the object you will be analyzing and make it current, for example “RN”. You can do the same simply selecting the desired object from the “Object menu” on the left side from the “Set object” menu.
4. Activate the segmentation window (the large window on your left) by clicking on it.

5. Select: Edit- Region of interest (ROI) – ROI tool On. Doing so you activate the ROI tool bar on the right side of the general toolbar.

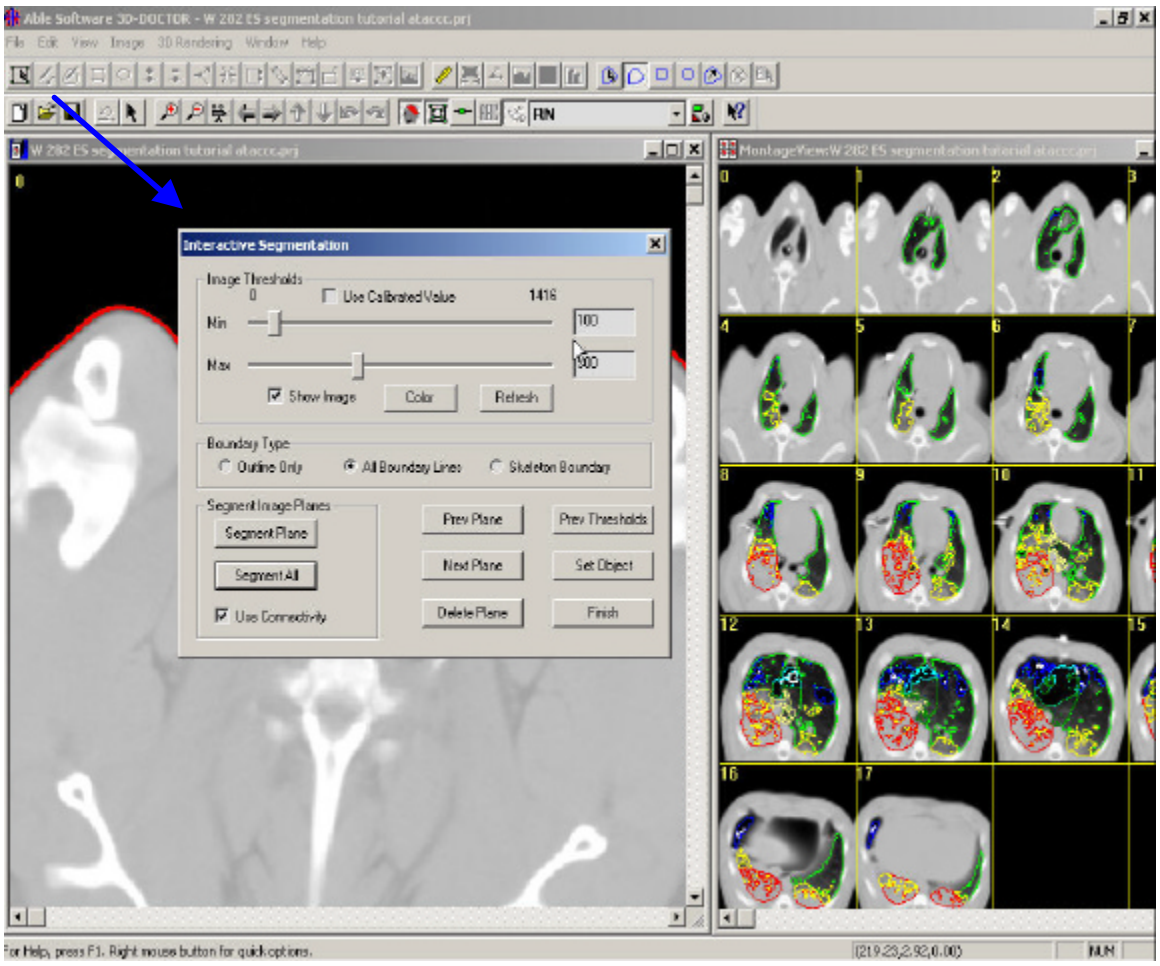


The same result is achievable by a right-mouse click.

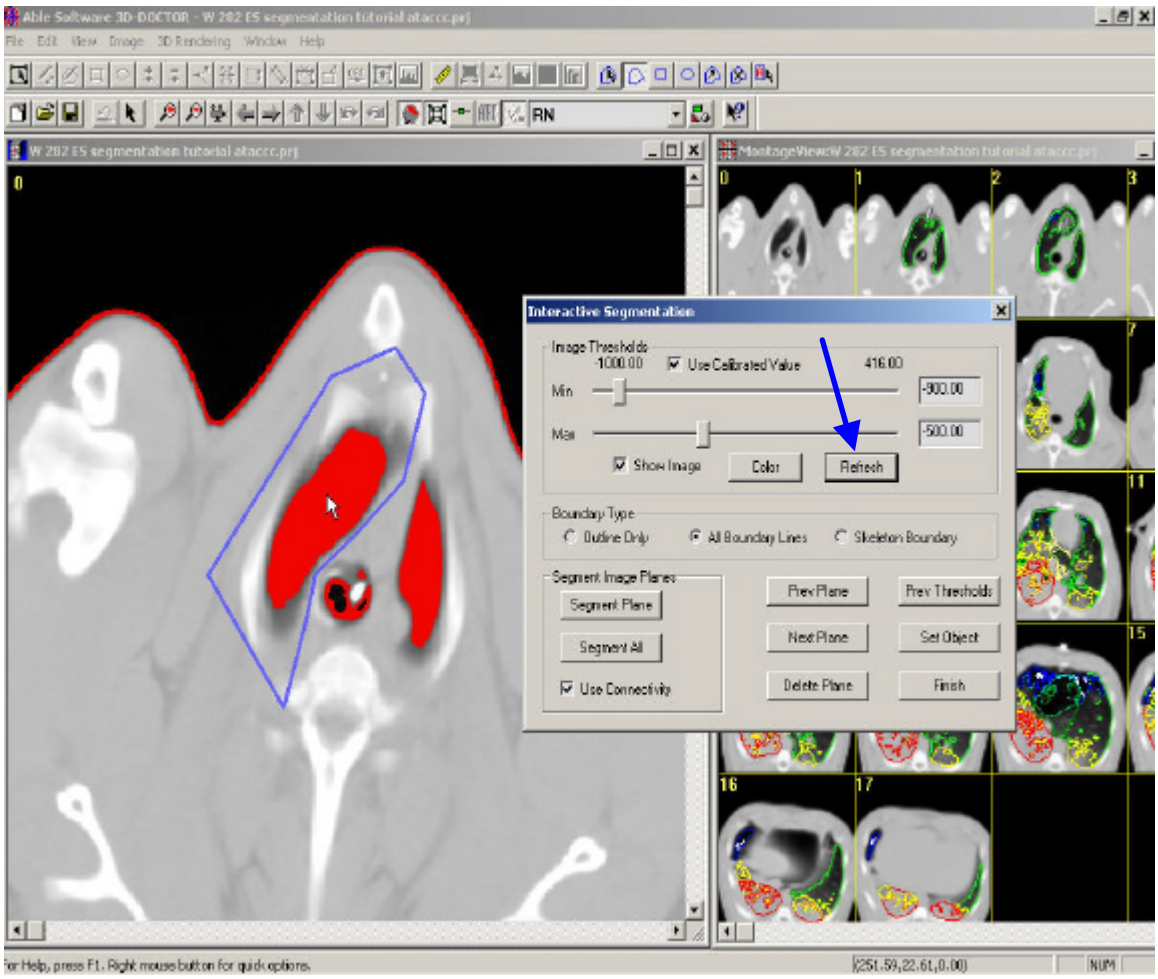
6. Select “Polygon” mode as it is the most convenient to draw the ROI.
7. Draw the ROI around the area of the lung to which the selected object corresponds. In our case RN is right lung. Do draw the ROI left-click on the mouse drag the line to the desired direction and left-click again when a direction change is needed. To connect the last two points and close the polygon press any key of the keyboard. For the normally aerated lung there is no need to draw a precise ROI including only the lung tissue. As the attenuation window (HU)

values for the normally aerated lung are different from those of the surrounding tissues the segmentation algorithm will pick up only the areas of specified HU values.

8. Click on 3 D Rendering- Interactive segmentation, to open the "Interactive segmentation window".

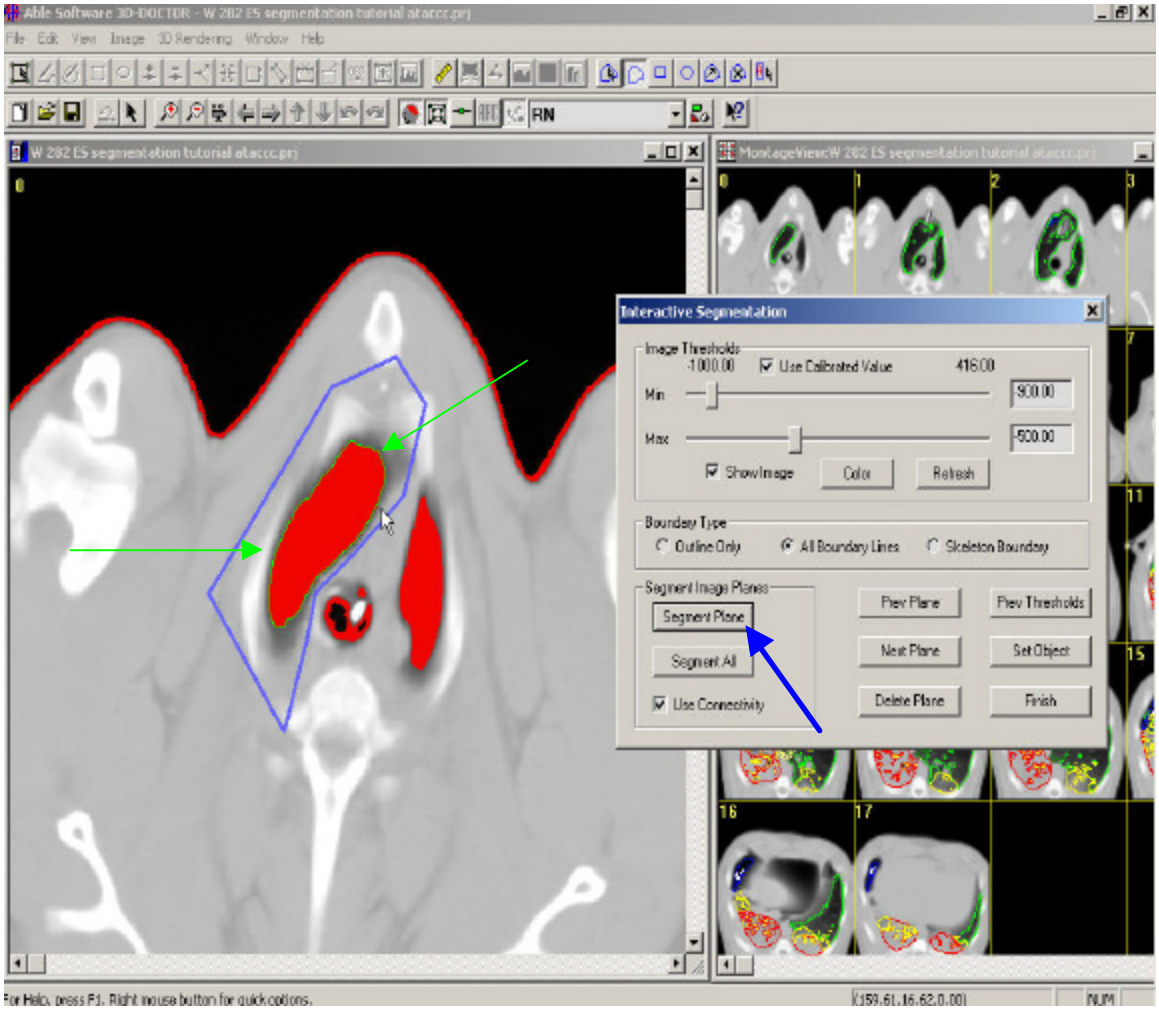


9. In the “Interactive segmentation” window the following settings should be checked: “use calibrated values”, “all boundary lines” and ”use connectivity”. In the Image threshold window set the HU window corresponding to the Object you are analyzing. For RN it is – 900 to – 500. Click on the refresh button. You will see the HU window applied to the ROI.



Also, if you have not set the object to be analyzed yet you can do it from the Interactive segmentation window by clicking on “Set object”.

10. Click on “Segment plane”. The pre-selected color- and line-type boundary for the object being analyzes (in this case RN) will be applied to the ROI (green arrows).



This finishes the segmentation for the particular object within this slice.

11. Click on “Next plane”. Your previously drawn ROI will be superimposed to the next slice. If the ROI covers all areas of interest you can simply click on “Segment plane”. If the ROI does not cover the desired area in full, click on “Finish” to make the Object management window disappear, than right click on the segmentation window and choose “Clear ROI”. Repeat from step 5 and draw a new ROI. Another option of adjustment of the ROI to the next slice is pressing on

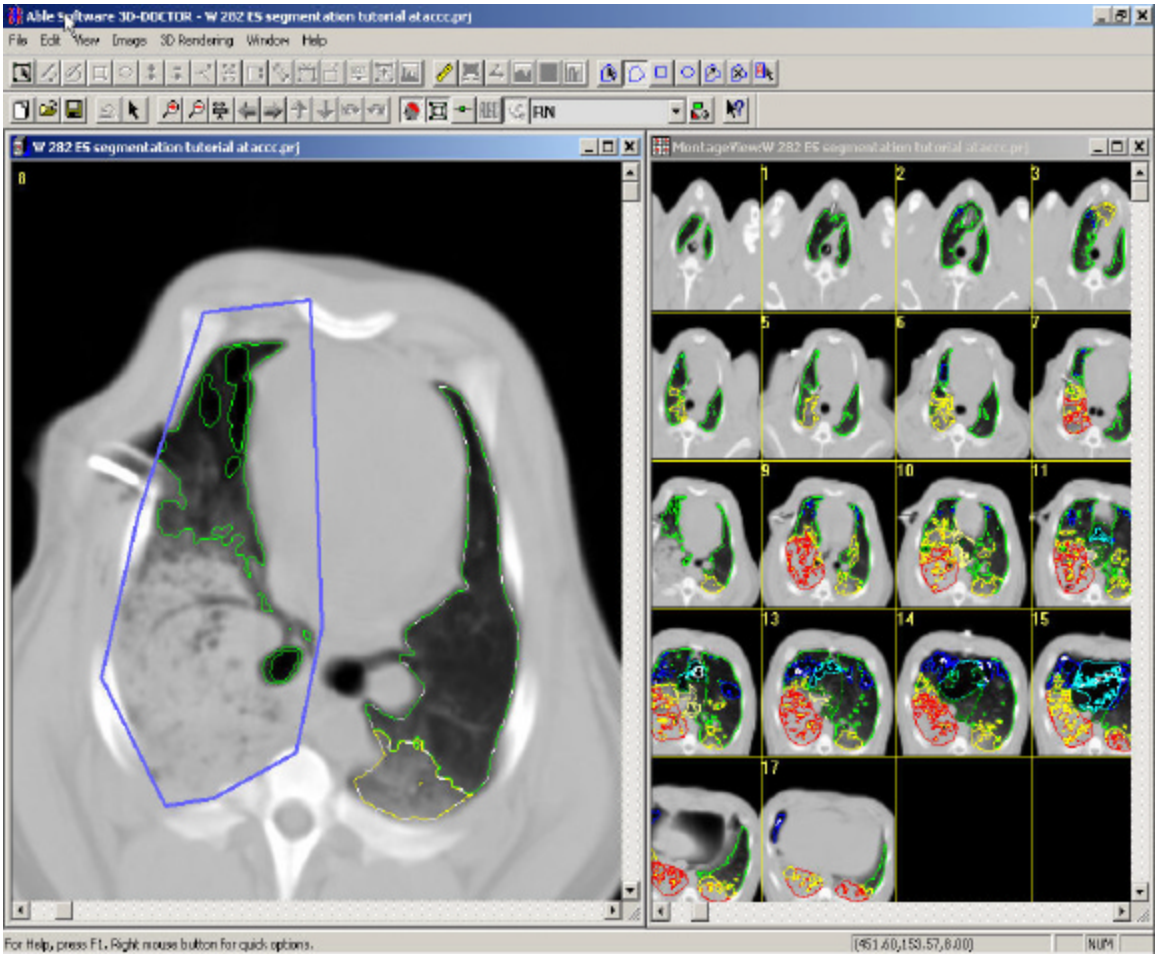
key “F7”, that will inflate (make the ROI expand) the region, or “F8”, that will deflate the region.

In a fashion, similar to the described above you can analyze the left lung and proceed to the next slice.

When segmenting areas with different HU window settings the approach should be analogous however the ROI drawing should involve only areas within the lung tissue to avoid including other areas where by coincidence the HU range is similar.

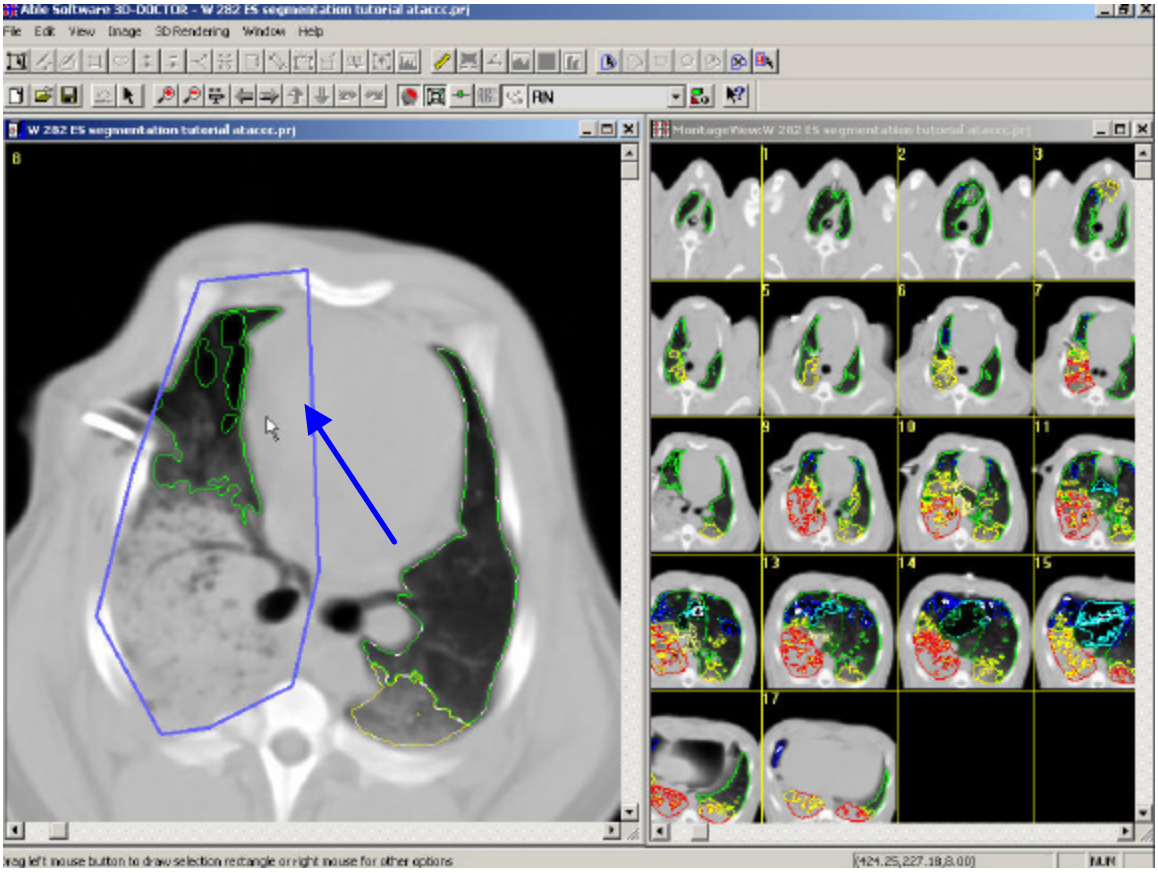
Here follows an illustration of segmentation done for normally, poorly, non-aerated and hyperinflated regions with comments on manual editing.

1. Normally aerated areas.



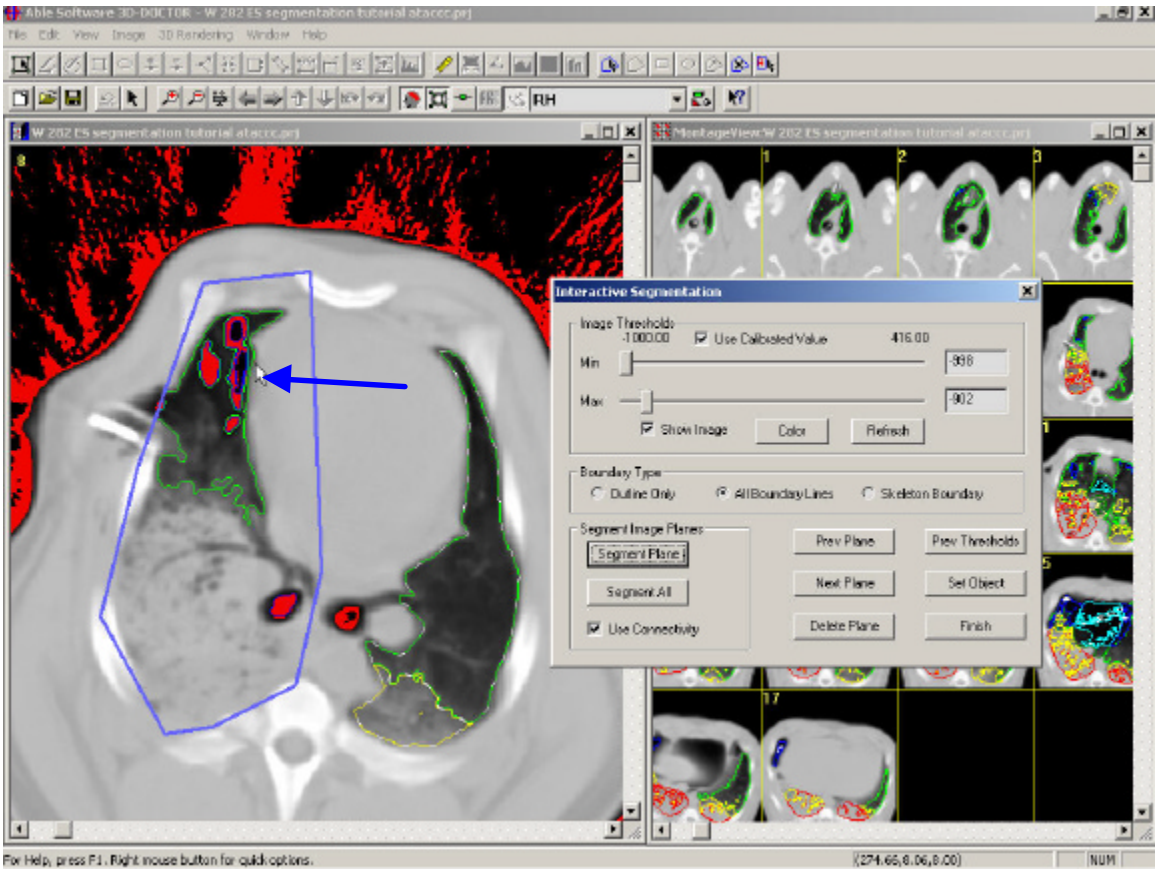
In this case some manual editing is necessary. To do that, click on the “Boundary editor” icon in the toolbar or click on “Edit”/“Boundary editor”/ “On”. Next, right-click on the segmentation window and choose “Delete boundary” or other tool needed for the editing. When you choose delete boundary the cursor becomes target –shaped and by clicking on the part of the image will delete the most adjacent boundary.

<u>Important note</u>: If 2 boundaries of the same HU window are found within a singe ROI, one inside the other, like in <u>this case</u>



the outer most boundary is active. This means that the area between the outer area and 3 boundaries inside is included in the analysis and the area inside the inner boundaries is excluded. This trend follows the parity rule. Namely, areas inside odd numbered boundaries counted in an outward-inward direction are active and inside even numbered boundaries are inactive. In the depicted case the outer boundary is active and all areas between the outer and inner boundaries will be included in the analysis. The area surrounded by the inner boundaries will be excluded as they contain zones of differing HU value. See the next demonstration below.

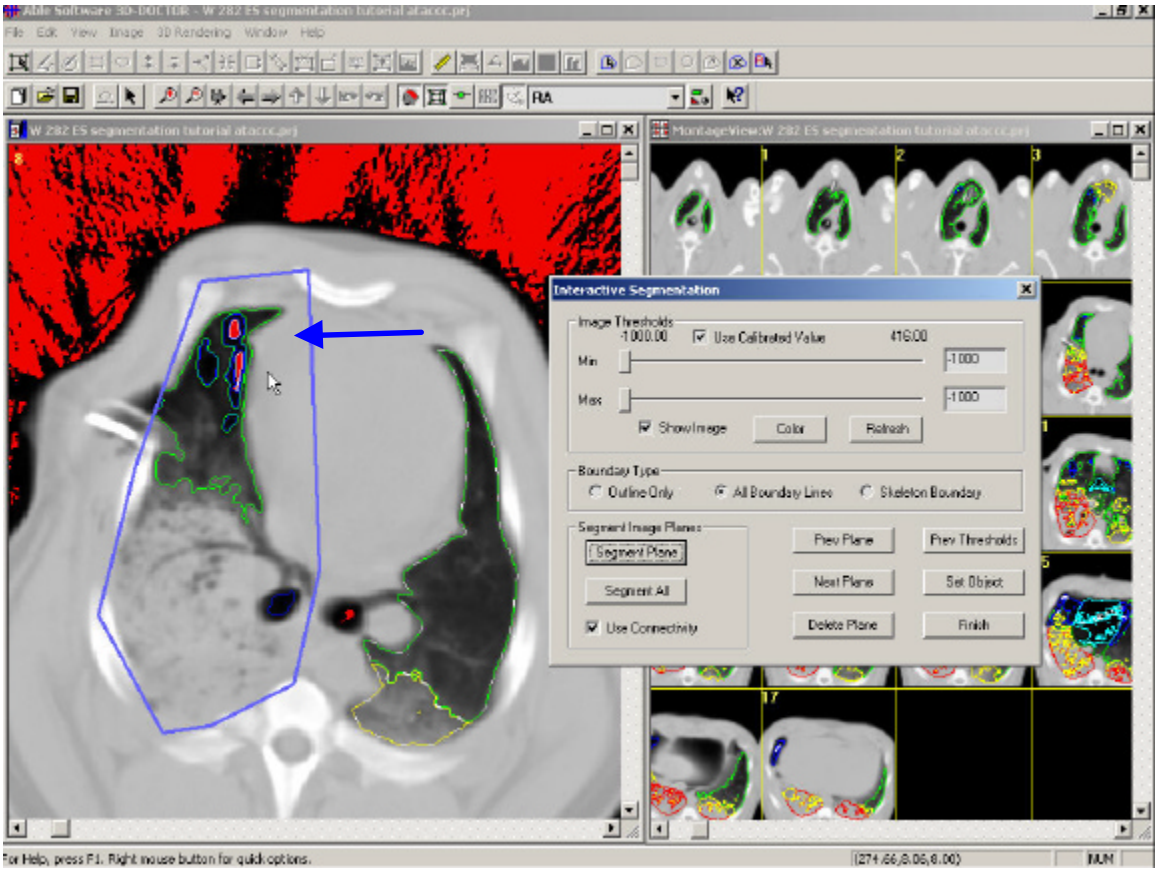
2. Hyperinflated areas.



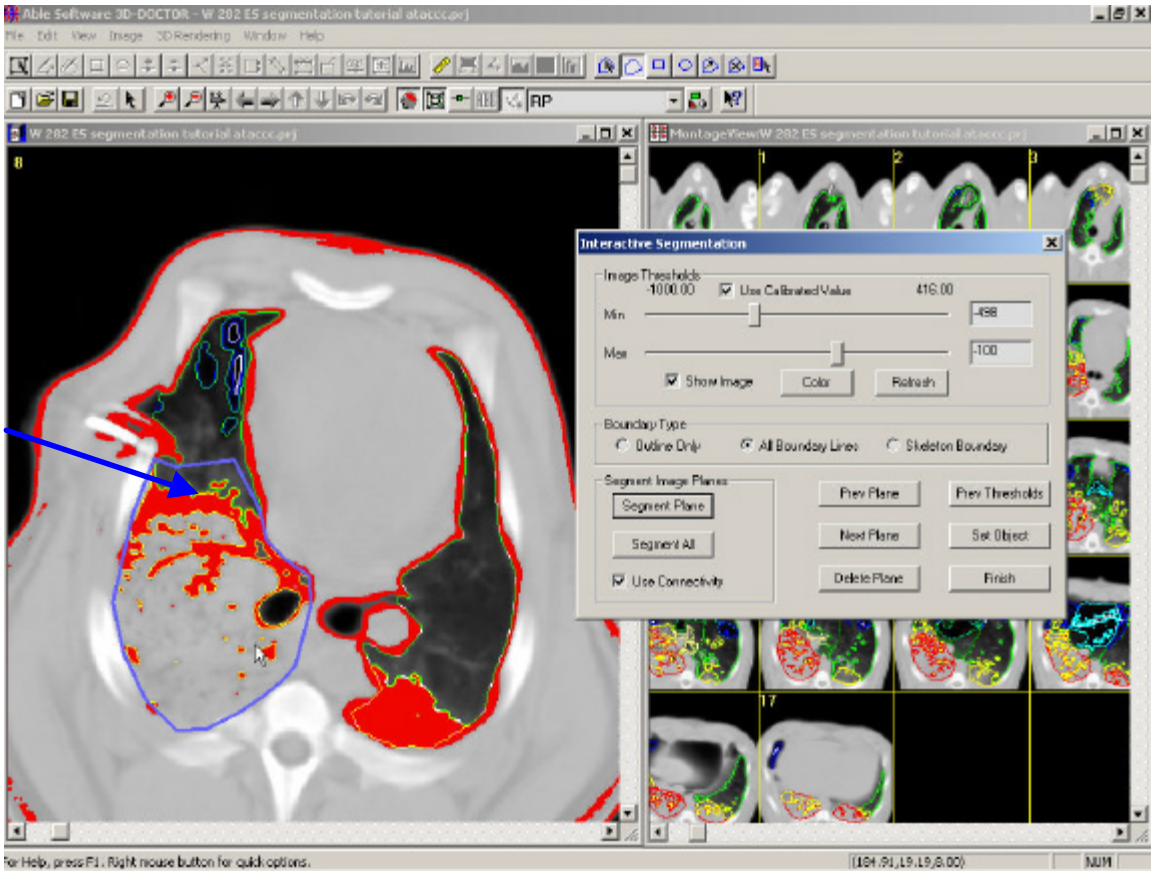
These lie within the “Normally” aerated areas and most of the times,

morphologically, represent emphysematous cysts or pneumatoceles.

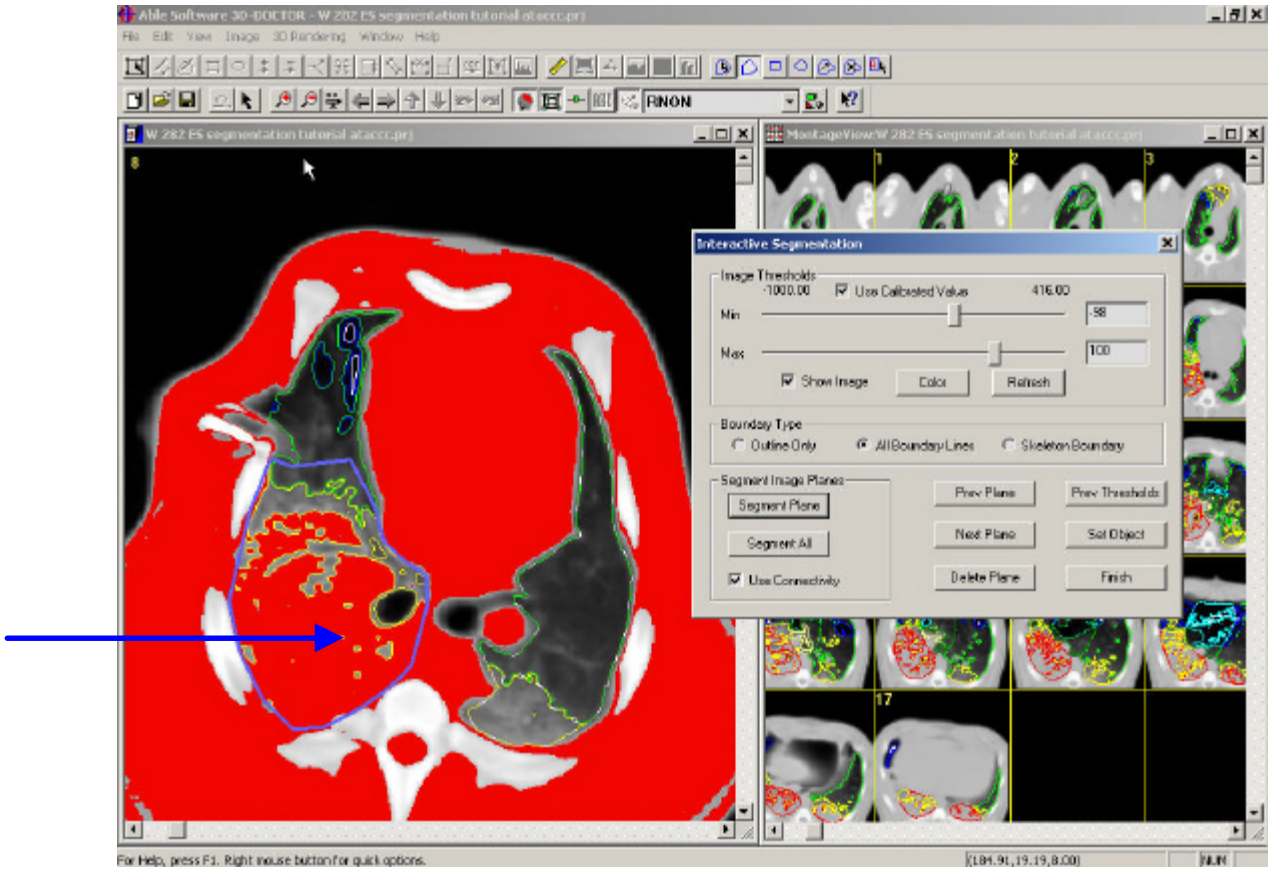
3. Air.



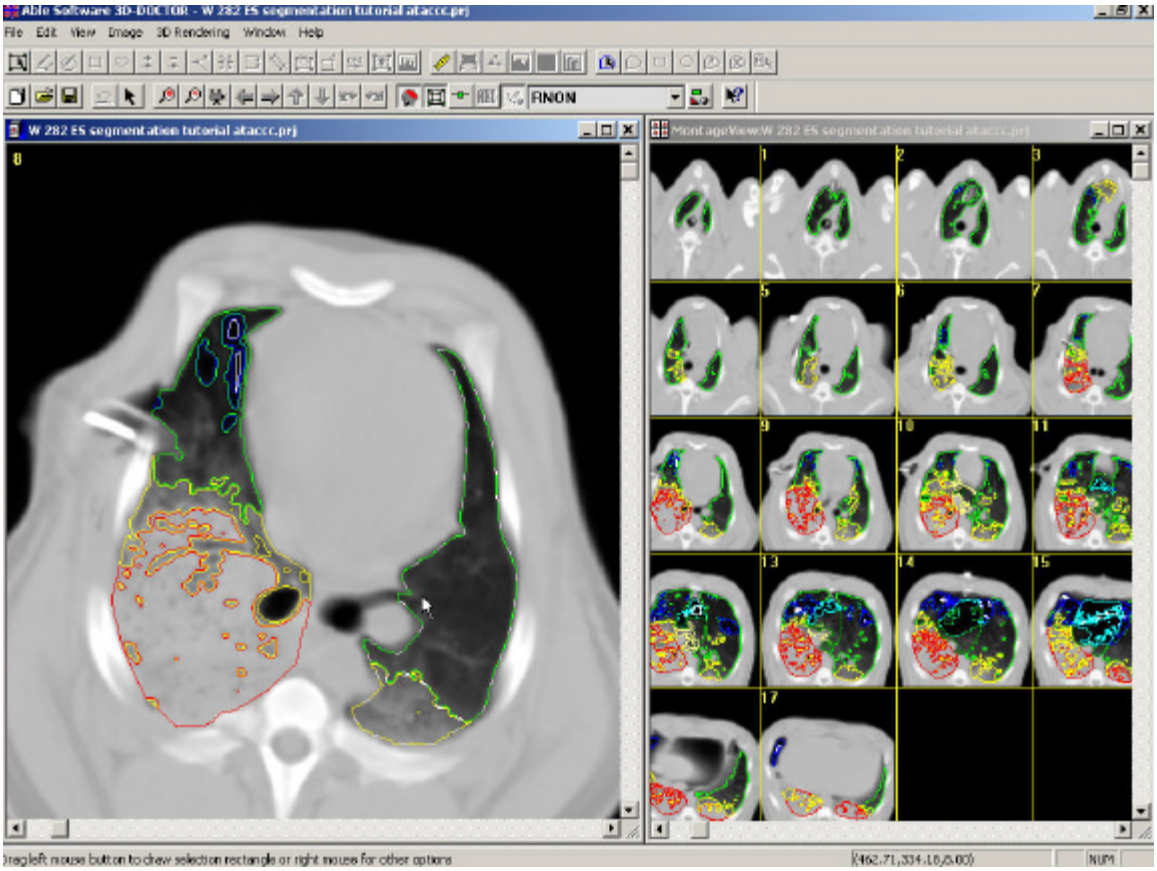
4. Poorly aerated.



5. Non-aerated.



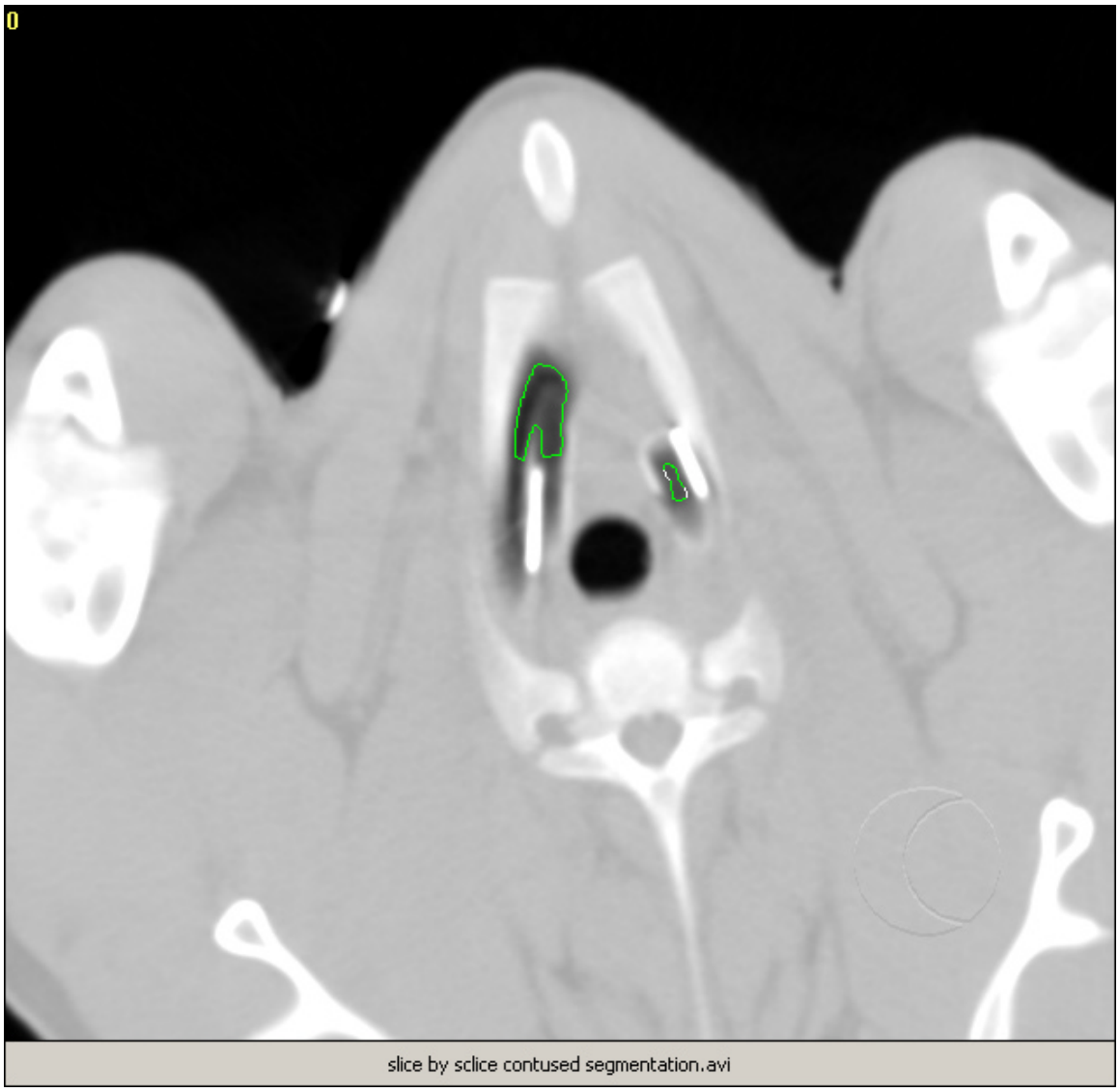
6. [Final result after manual editing.]



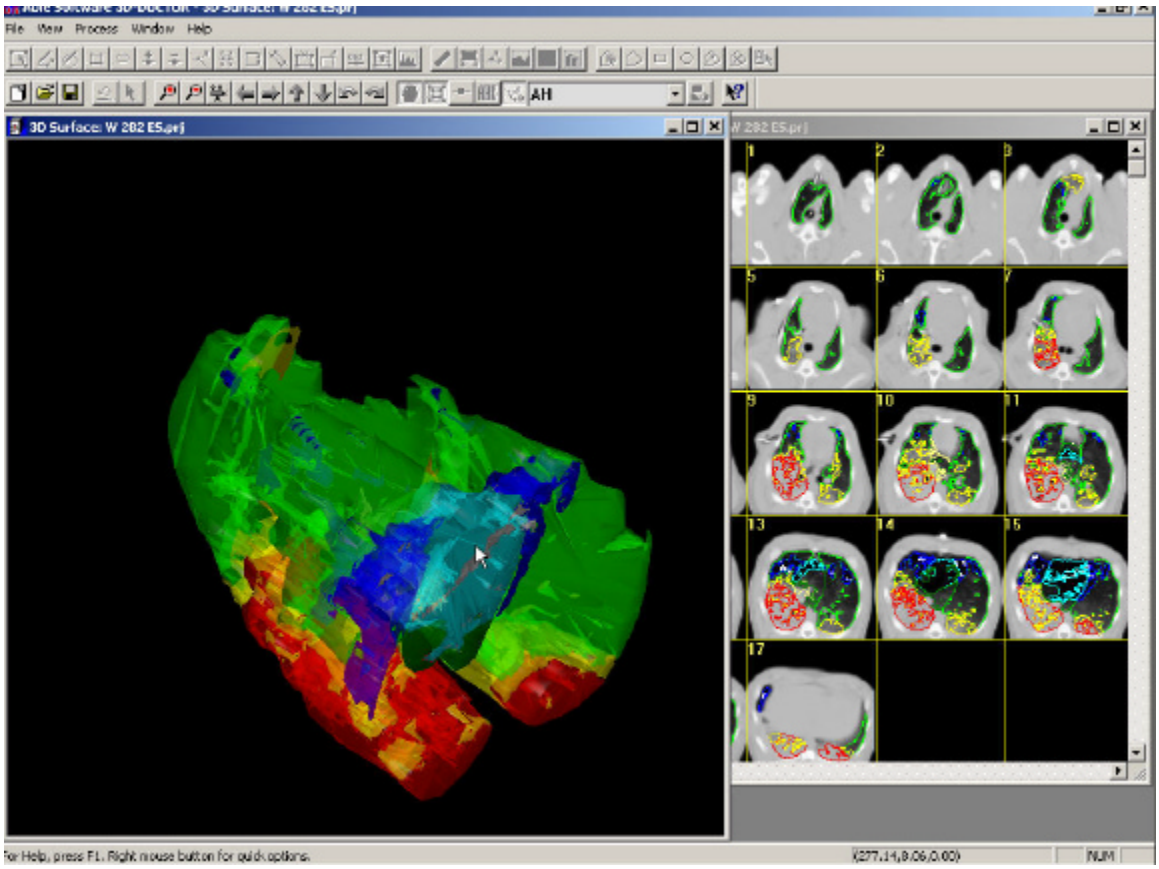
Repeating the analysis with respect to each aeration zone within each lung for every slice, one will get the whole stack analyzed. Now you are ready for the 3 D reconstruction part.

Part 3: 3-d reconstruction of the segmented image stack

After you complete the slice-by-slice segmentation save your work to the project file. The final segmented slices can be viewed in the montage window and will look as depicted in this animated clip. See below. Demonstration in the multimedia version.



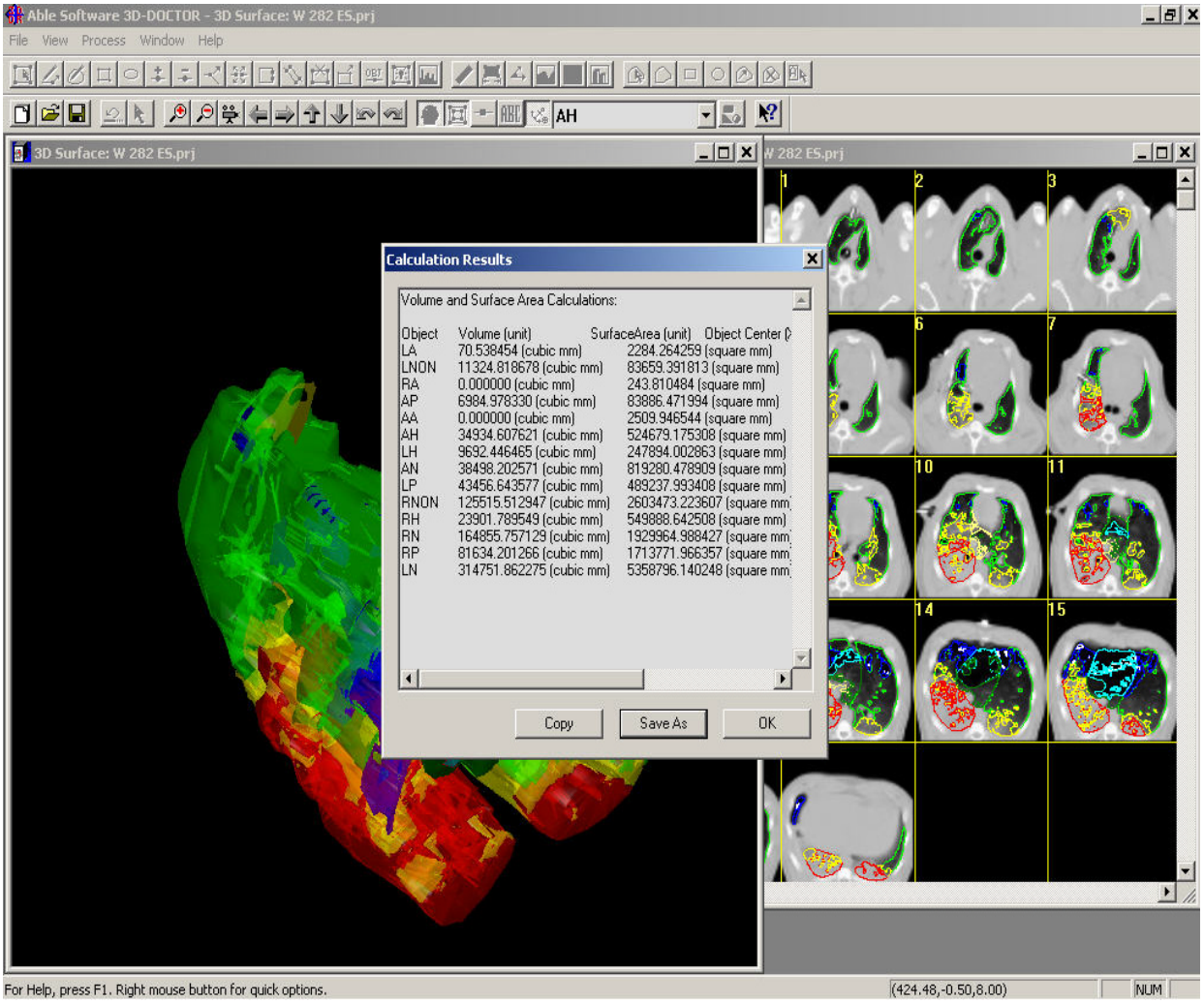
In the next step we will use one of the rendering algorithms available from the 3 D Rendering / Surface rendering menu. For purposes of 3 D reconstruction, any of the available algorithms is usable. However, if accurate volume calculations are to be made the Simple surface rendering should be used. To launch this algorithm, go to 3D Rendering / Surface rendering / Simple Surface. The rendering takes various amounts of time depending on your PC's computing power and the complexity of the segmented areas. The resulting file of your rendering will appear in a separate window (Example) and can be saved as a separate "surface file" selecting File/Save surface. See below.



Data Outputs

The rendered object can be analyzed with respect to variables given below.

By selecting Process/ Calculate volumes



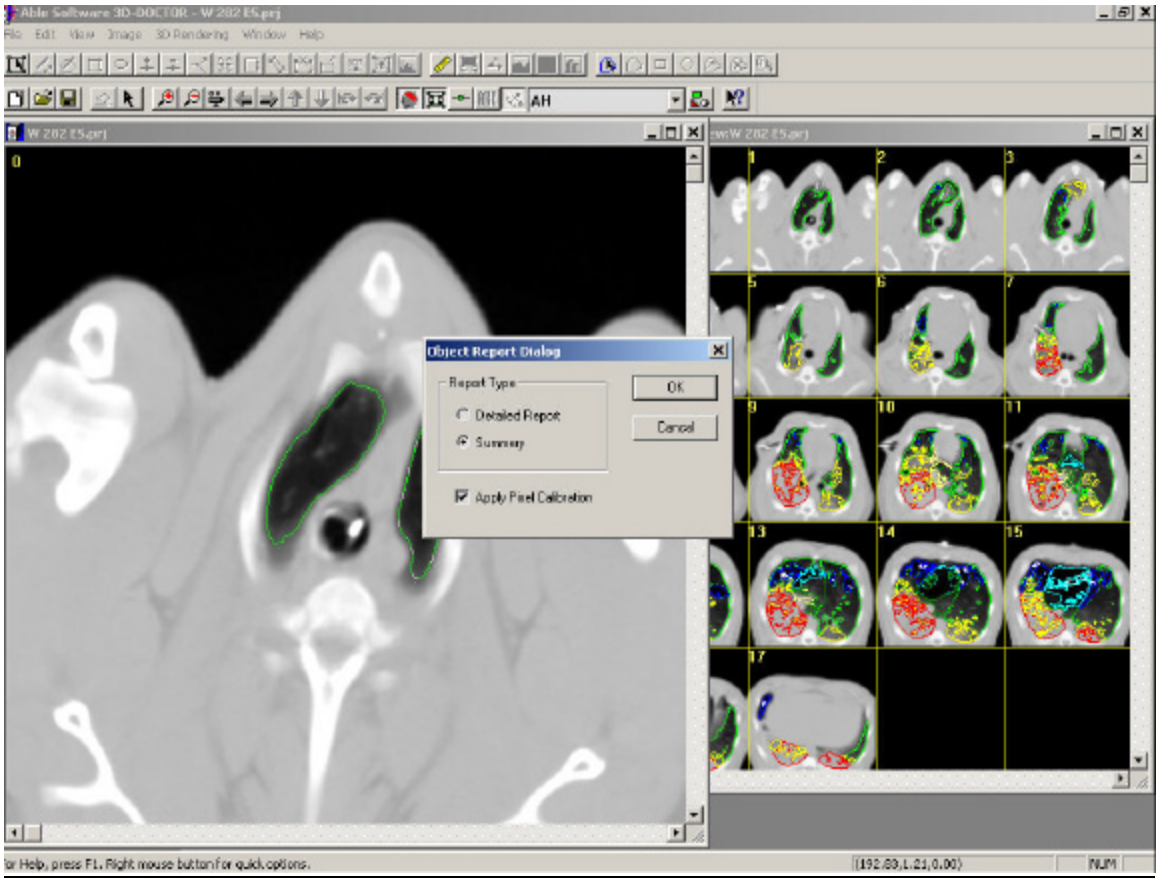
- Volume of each object represented in cubic millimeters
- Surface area for each object represented in square millimeters
- Orientation of the object center in space

The output file can be saved and exported into a database as a whole or via cutting and pasting the necessary information into an Excel workbook.

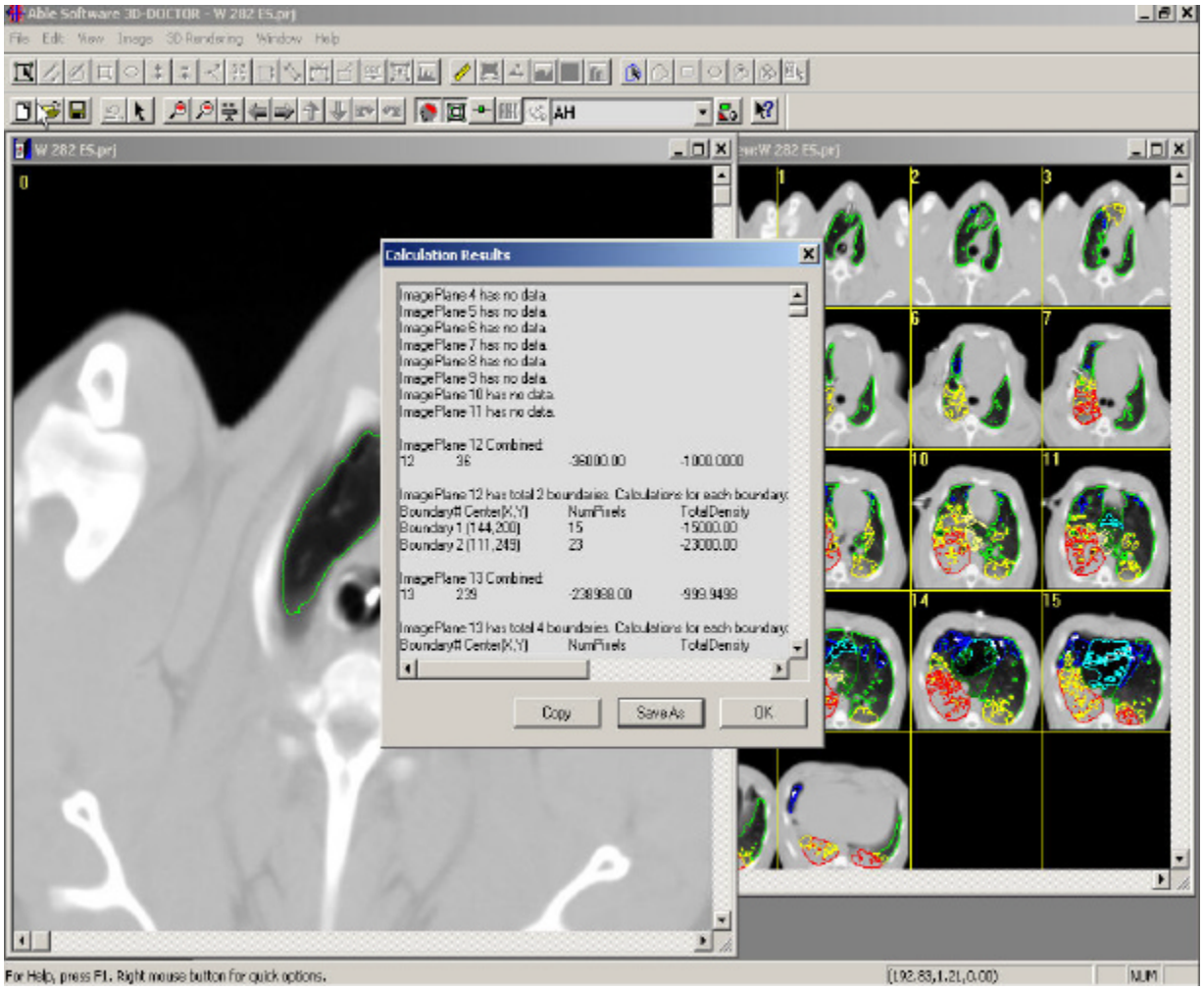
After every image plane was segmented the following data can be obtained: (it is not required to perform 3-d rendering to obtain this data).

By selecting Edit/ Object report.

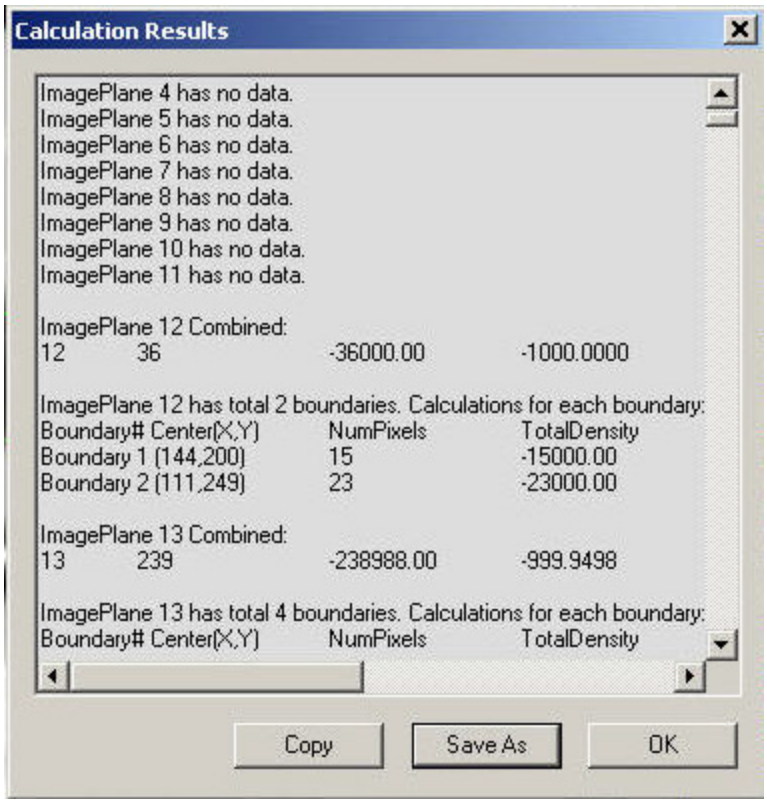
In the proposed pop-up menu (Object report dialog box) always check the “Apply pixel calibration” box before clicking “OK” in this Object report dialog. By this, the software follows the inherent calibration of the DICOM image stack imported from the source file.



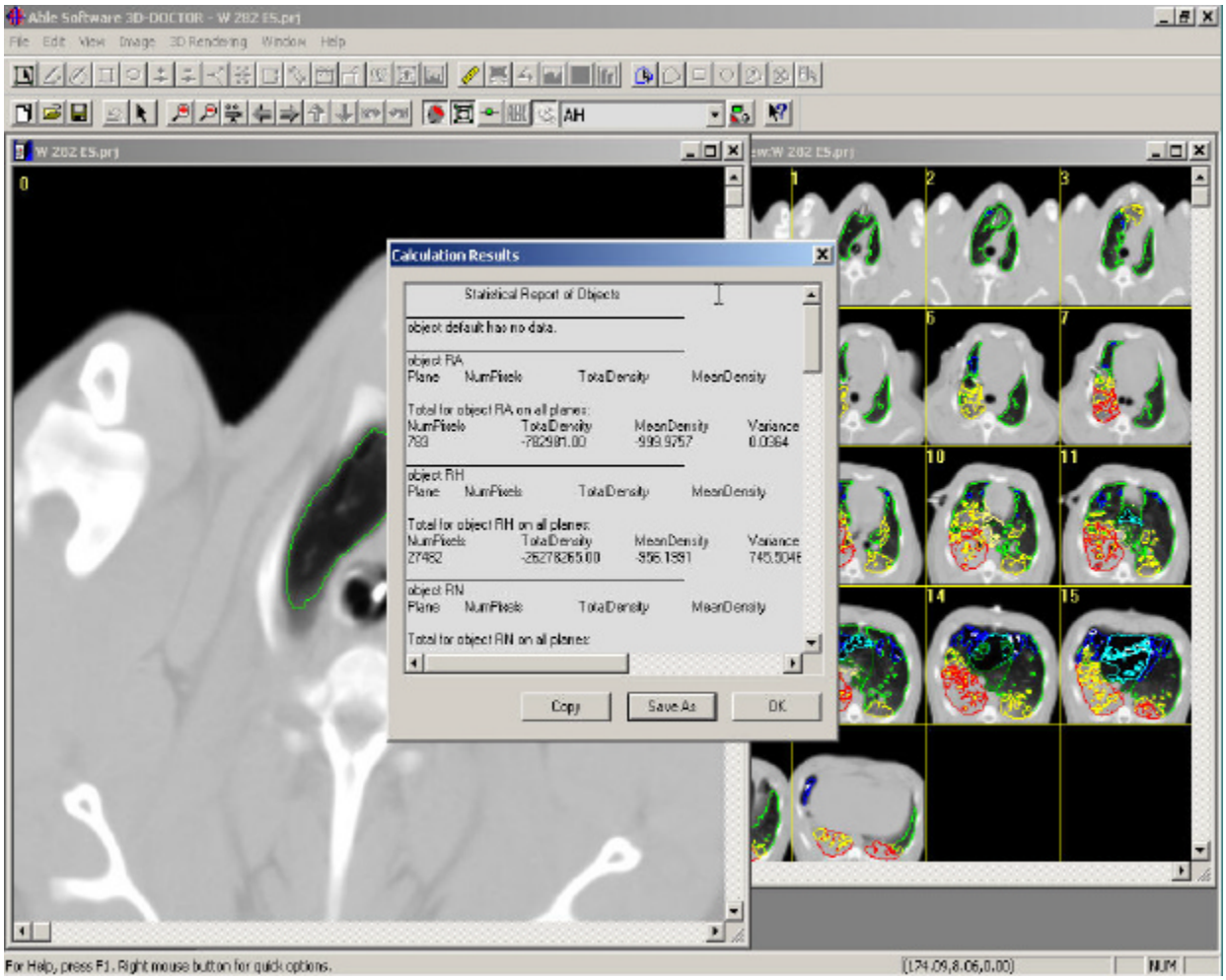
Choose Detailed report output if you are looking for evaluation of each boundary.



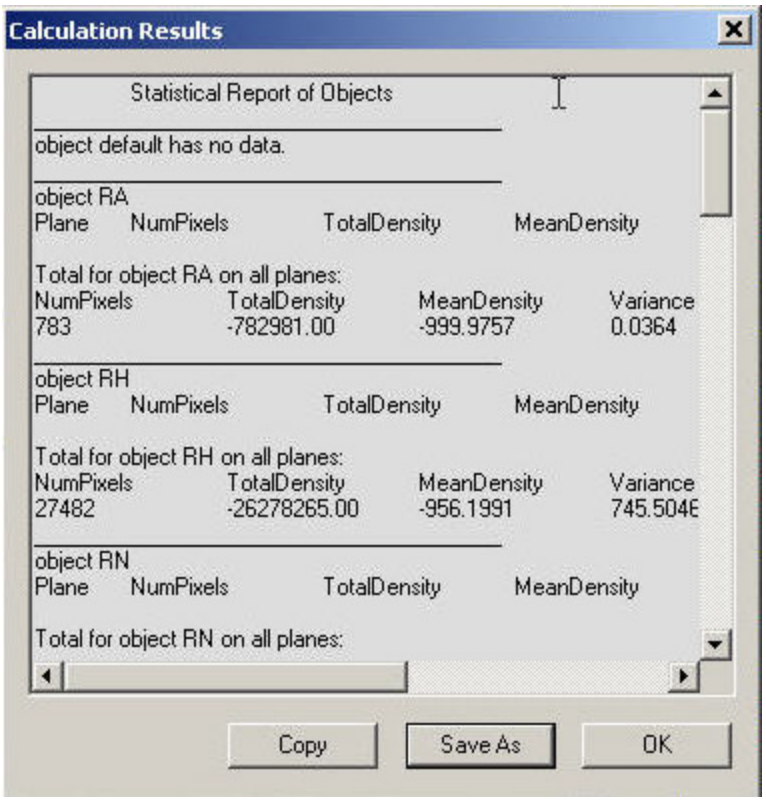
If you choose detailed report the calculation results will look like this:



Choose Summary output if you are interested in values by object only. The latter used in our study.



If you choose “Summary” output the calculation results will look like this:

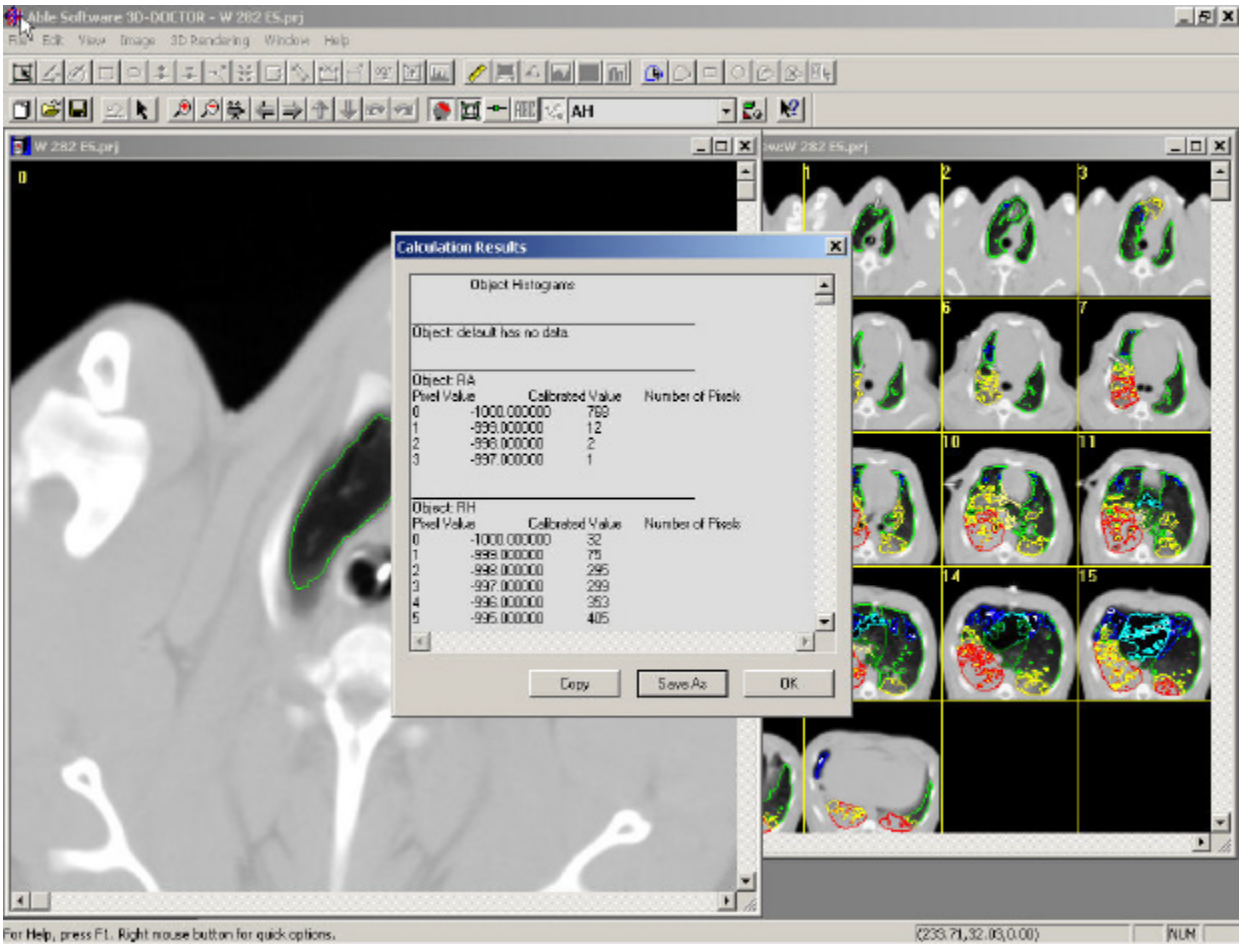


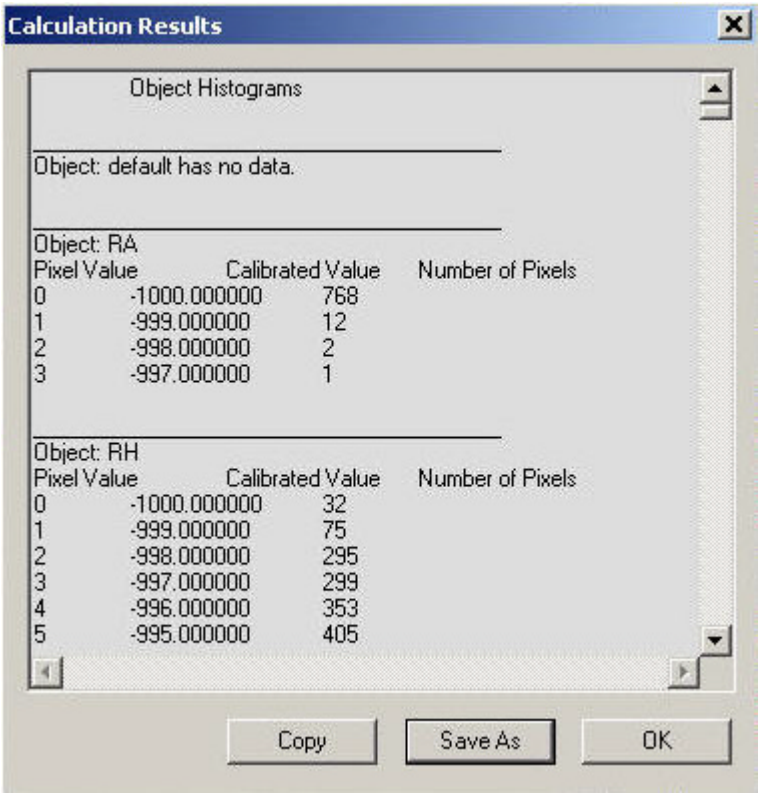
The data outputs in the Summary mode are:

- Total number of pixels for a given object on all planes analyzed
- Total density of the object
- Mean density
- Variance
- Minimal density value
- Maximal density value

The data output in the “Detailed” mode gives the same values broken down by planes and boundaries.

By selecting Edit / Object histogram


Able Software 3D-DOCTOR - W 282 ES.prj
File Edit View Image 3D Rendering Window Help
AH
W 282 ES.prj
Calculation Results
Object Histograms
Object: default has no data
Object: RA
Pixel Value Calibrated Value Number of Pixels
0 -1000.000000 788
1 -998.000000 12
2 -996.000000 2
3 -997.000000 1
Object: RH
Pixel Value Calibrated Value Number of Pixels
0 -1000.000000 32
1 -998.000000 75
2 -998.000000 295
3 -997.000000 299
4 -996.000000 353
5 -995.000000 405
Copy
Save As
OK
For Help, press F1. Right mouse button for quick options.
(233.71,32.03,0.00)
NUM



you will get data on:

- Pixel value
- Calibrated value corresponding to each pixel value for the given object
- Number of pixels with the given value within the object

All data outputs can be saved as separate files.

As end points of our study we used:

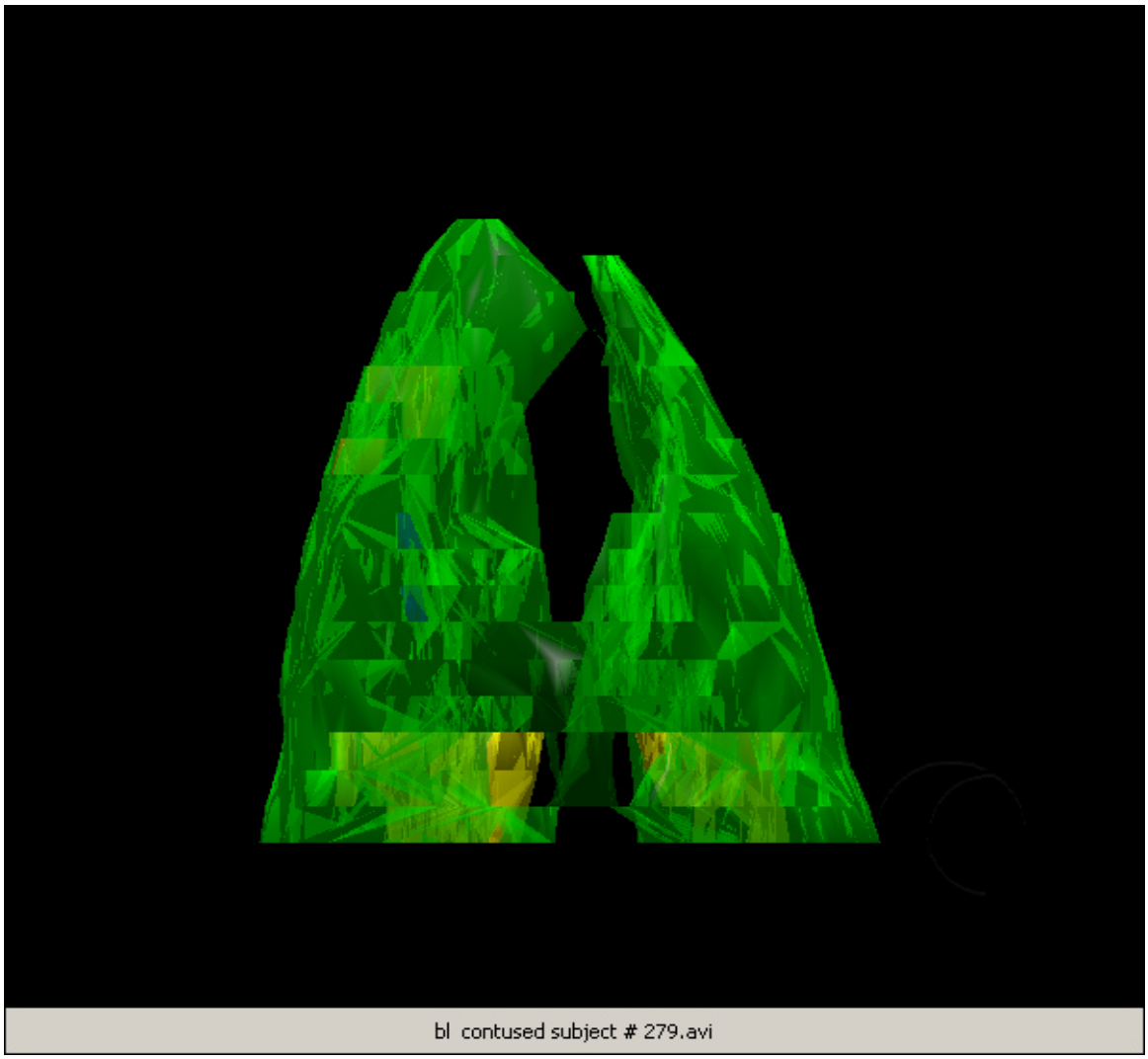
- Mean gray-scale density of the lung as a whole (MGSD) from the Summary output of the Object report.
- Fractional lung volumes: e.g.

  Fraction Poor = (Volume of Poorly Aerated Lung)

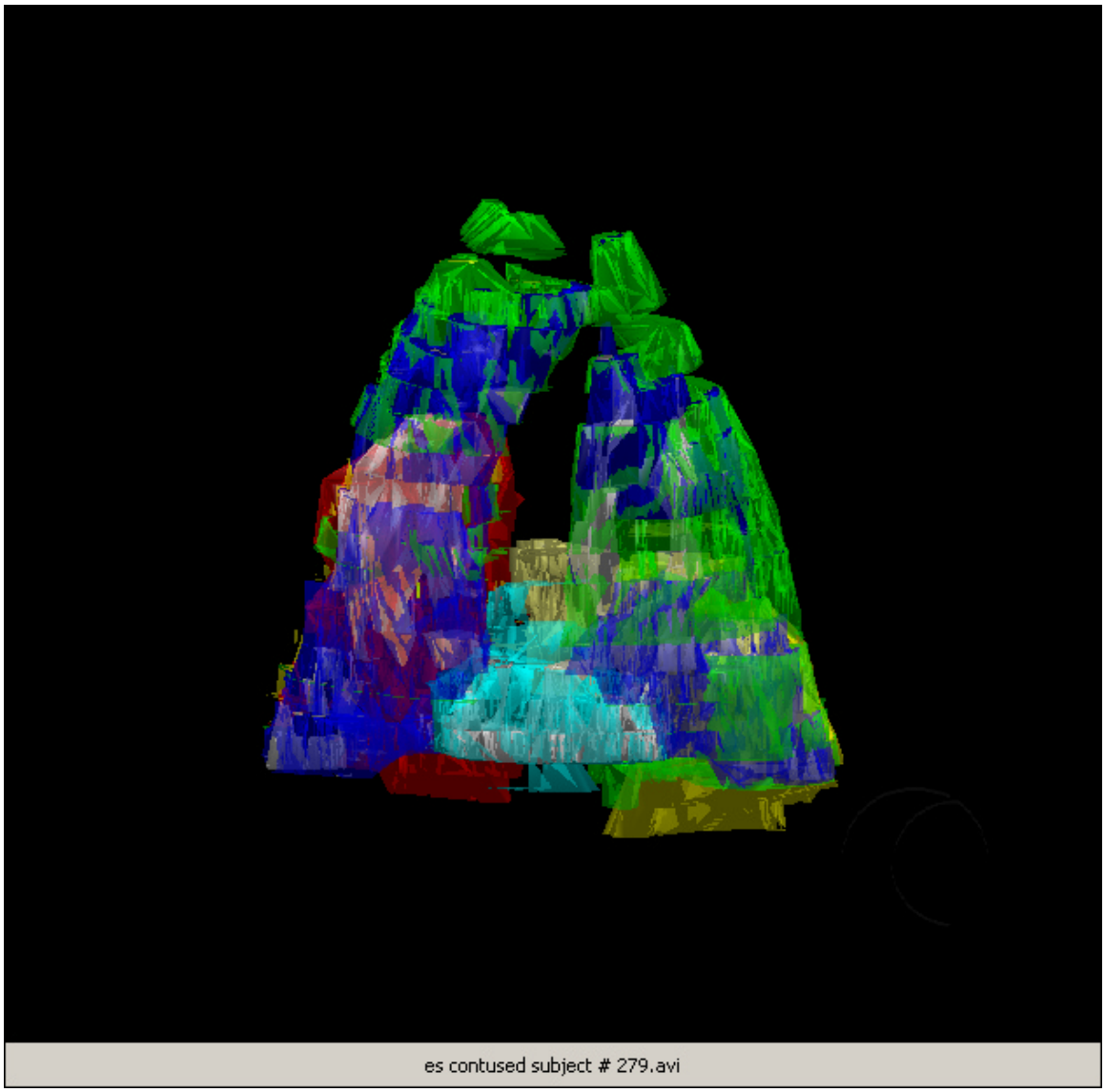
  (Volume of Entire Lung)

- 3-D depiction performed for illustration

Animated depiction of a 3-d reconstructed surface file of a subject at baseline of the study. To view (in the multimedia version), click and then double- click on the area below.

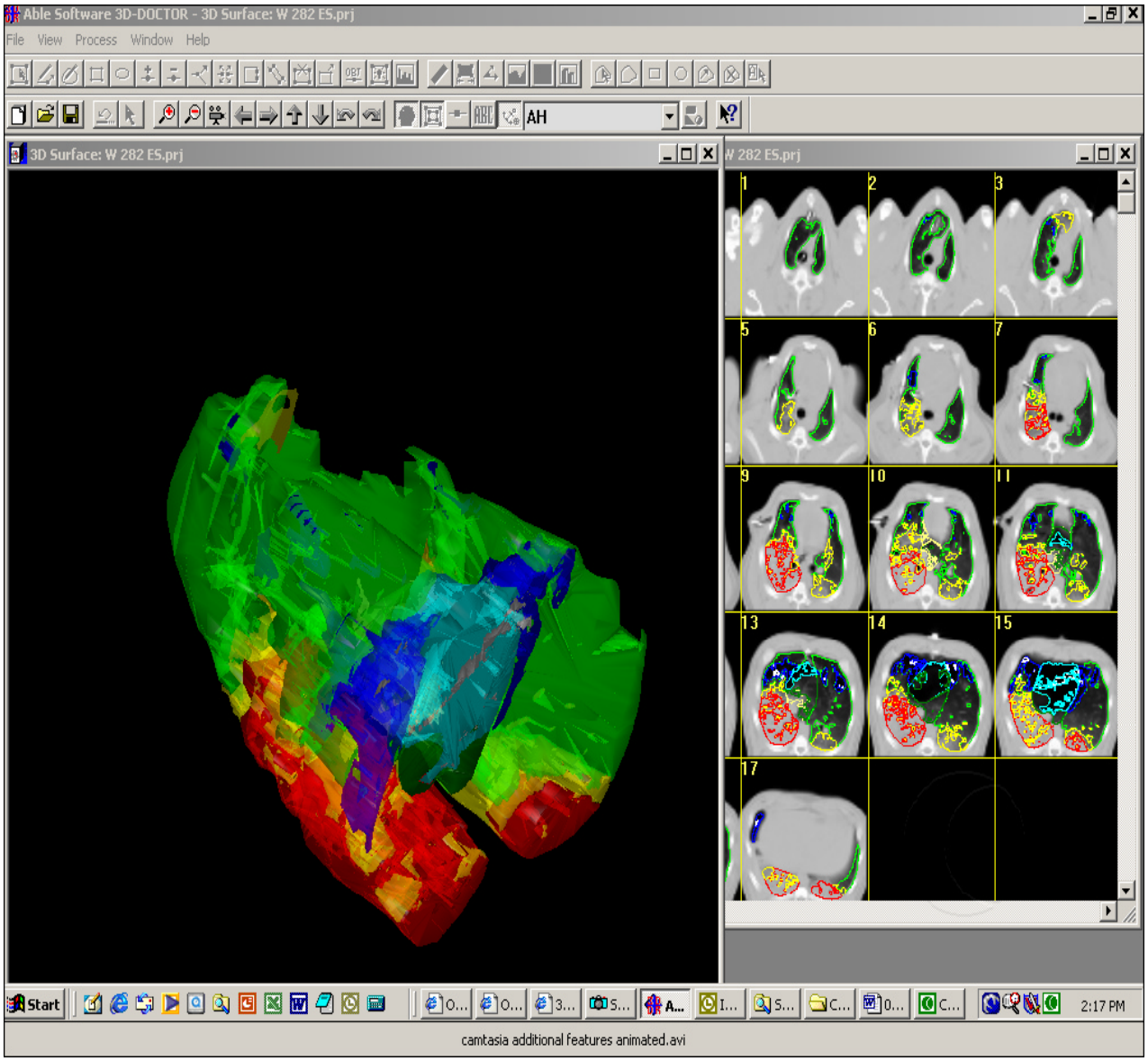


Animated depiction of a 3-d reconstructed surface file of the same subject at completion of the study i.e. 6 hours post pulmonary contusion. To view (in the multimedia version), click and then double- click on the area below.



3- D Animation and Additional Features

To perform animation of the reconstructed lung all you need to do is press the animation button on the tool bar after you have the rendered lung displayed as a rendered surface. When you click on the “Animate” button you can choose the coordinates and define the orientation of the object when animated. Also, you can use a variety of displaying features offered by the menus to add cube. To view the demonstration(in the multimedia version), double-click on the space below.


Able Software 3D-DOCTOR - 3D Surface: W 282 ES.prj
File View Process Window Help
AH
3D Surface: W 282 ES.prj
W 282 ES.prj
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camtasia additional features animated.avi

Discussion: Potential Military and Clinical Relevance

In a prospective study involving humans who sustained pulmonary contusion, Fabian et al. proposed a three-dimensional reconstruction approach to provide an accurate measurement of the contusion volume relative to pulmonary function and outcome. The fraction of contused lung tissue was determined as the ratio of contused lung volume to total lung volume. It was postulated that the extent of contusion volumes measured using three-dimensional reconstruction allows identification of patients at high risk of pulmonary dysfunction as characterized by development of adult respiratory distress syndrome (ARDS). In this study, which is the only one in the literature on measurement of pulmonary contusion volume based on 3-D reconstructed CT scans, the group found that 50% of patients in the severe group (more than 20 % contusion volume) developed pneumonia as compared to 28% in the moderate group (less than 20% contusion volume). The authors concluded that the method of measurement might provide a useful tool for the further study of pulmonary contusion as well as for the identification of patients at high risk of complications for whom future advances in therapy may be directed. The group used the 3Dvirtuoso (Siemens Health Services, Erlangen, Germany) software package to complete their study.

Hence, the algorithm we used in our study could be potentially used for high volume CT scan analysis, treatment and prognosis in trauma centers as well as in military settings. The military applicability of this approach seems even more promising with the

expected increase of behind-armor injuries due to wide use of protective gear on the on the battlefield.

It is conceivable that after further refinement a low-cost and accurate density-based morphological evaluation and diagnostic tool could be developed and a well-controlled multicenter trial would give the ultimate answer concerning the feasibility of semiautomatic CT scan evaluation and diagnostics. At present the method described here is available for use in conjunction with animal and clinical research protocols.

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